Regional Hydrodynamic and Wave Transformation Modeling – 60% Design – Layout Optioneering and Sediment Transport Modeling

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The Nature Conservancy
Tyndall Air Force Base Pilot Project Design and Permitting

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Jacobs

25 West Cedar Street
Suite 350
Pensacola, FL 32502
U.S.

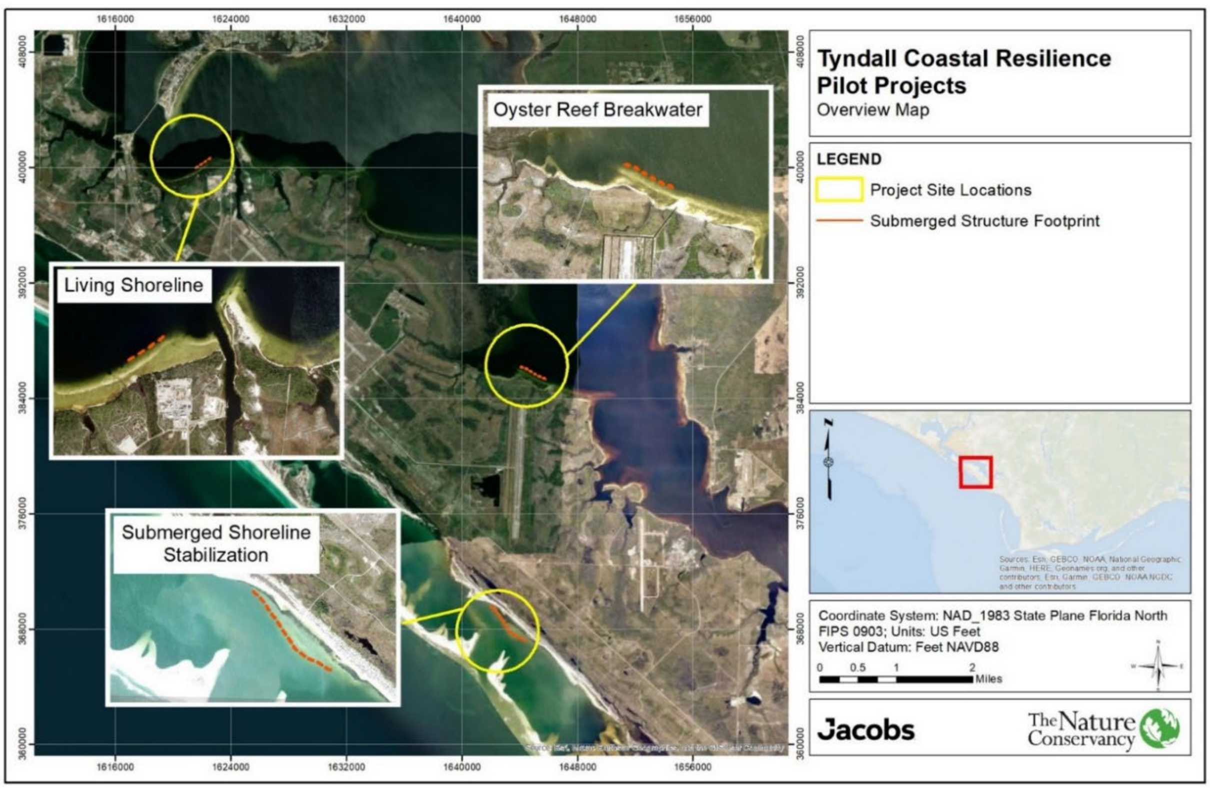
T +1 850 438 2740
www.jacobs.com

Executive Summary

The present study is a follow-up to the previously completed 60% design stage for calibrated models (Jacobs 2024) and builds on the previous study by focusing on the following primary tasks:

- To determine the annual sedimentation rates, annual sediment transport modeling was conducted on the existing conditions (baseline) at the three project sites. The three sites (Figure ES-1) are the Submerged Shoreline Stabilization site, located in the coastal area and protected by a barrier island broken by an entrance channel, an Oyster Reef Breakwater site, and a Living Shoreline site, both of which are located within the East Bay.
- The historical annual sedimentation rates were derived by annualizing the difference between two time-separated bathymetries, November 2022 and approximately 2010.The calibrated models are applied in wave attenuation analysis to assist in layout optioneering and arrive at the preferred layouts.
- Annual sediment transport modeling was conducted on the preferred layouts at the three sites to determine sedimentation impacts induced by the preferred layouts.
- The calibrated models were applied to determine extreme flows and waves associated with the preferred layouts for design optimization.

Figure ES-1. Location of the Project Sites and Associated Proposed Types of Protection Measures



Based on the historical sedimentation rates, the modeling estimated an average accretion rate of +0.05 meter per year, on the landward side of the projects. Further seaward, the area trends toward being slightly erosional at an average rate of up to –0.1 meter per year, except at the Submerged Shoreline Stabilization site where the erosional rate can reach up to –0.15 meter per year because the coastal site is exposed to larger waves due to the presence of the bay entrance.

The accuracy of the above modeled results could be potentially affected by the following three sources of uncertainty:

- Accuracy of the annual historical sedimentation rates used in model calibration
- Dynamic nature of the entrance bar to the Submerged Shoreline Stabilization site
- Interannual variation in the ambient wind climate, which is a significant driver for flows and waves that drive the movement of sediments

Wave attenuation of different layout schemes was investigated via quasi-stationary wave modeling where the crest elevation of the detached breakwaters is set at mean lower low water, which implies that the breakwater will be submerged below the water surface to varying degrees most of the time. Such a design leads to less design wave load and the use of less construction material, both contributing to cost savings. At the same time, higher waves will also be experienced in the lee and the impact of these potentially higher waves is investigated herein.

Generally, it is observed that increased water levels (that is, increased wave heights over the structure crest due to the greater water depth) decrease wave attenuation across all transects (that is, larger waves at the landward side of the structures). In addition, the combined action of the multiple gaps leads to varying low wave attenuation zones in the lee areas of the breakwater structures depending on the number of detached breakwaters and gap width, which potentially impact the sustainability of the submerged aquatic vegetation area.

The results of the wave attention analysis as a function of different layouts and water level variations were fed to the design team as inputs to their design optimization task. The preferred layouts for each site were applied in the subsequent sediment transport modeling and extreme flow and wave modeling for the preferred layouts.

These preferred layouts are as follows:

- Submerged Shoreline Stabilization: 12 segments of 200-foot-long straight submerged breakwaters spaced uniformly 100 feet apart along a curvilinear alignment.
- Oyster Reef Breakwater: Six segments of 200-foot-long curvilinear submerged breakwaters spaced uniformly 150 feet apart along a nearly straight alignment, where the leeward side consists of a series of finger spurs flanked by precast Defense Advanced Research Projects Agency units.
- Living Shoreline: Four segments of 200-foot-long straight submerged breakwaters spaced uniformly 150 feet apart along a shore with a parallel straight alignment.

The impacts of the proposed structures were evaluated via sediment transport modeling related to those for the existing condition. For the Submerged Shoreline Stabilization site, the impacts include the following:

- The nearshore sedimentation rate is enhanced to the tune of 0.1 meter per year on average, which is likely due to wave sheltering.
- The belt of erosion abutting the landward edge of the structure results in an enhanced erosion rate up to as much as -0.1 meter near the center of the structure line.
- There is now a sedimentation strip immediately seaward of the structure line of up to 0.05 meter per year.

For the Oyster Reef Breakwater site, the impacts are as follows:

- The overall changes are minimal except for some shifting discrete zones around the structure line of sedimentation and erosion, which are essentially maintaining the same annual rates of +/-0.05 meter per year.

For the Living Shoreline site, the impacts are as follows:

- The overall changes are minimal except for slightly enhanced sedimentation and erosion rates of up to +/-0.1 meter per year.

Extreme hydrodynamic and wave modeling were conducted to determine the design flow and wave conditions required for the detailed design of the proposed structures. The simulations were performed for the adopted design storm events (that is, 50 years for the Submerged Shoreline Stabilization site and 25 years for the Oyster Reef Breakwater and Living Shoreline sites).

If the design team needs to refer to the results further, they are presented as spatial distributions of maximum current speeds and wave heights.

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Acronyms and Abbreviations

°	degree(s)
AFB	Air Force Base
DARPA	Defense Advanced Research Projects Agency
DEM	digital elevation model
HD	hydrodynamic
m	meter(s)
MHHW	mean higher high water
MLLW	mean lower low water
NAVD 88	North American Datum of 1988
NCEI	National Center for Environmental Information
NOAA	National Oceanic and Atmospheric Administration
SAV	submerged aquatic vegetation
SLR	sea level rise

1. Introduction

Tyndall Air Force Base (AFB) is located in Bay County, Florida, which is landward of the barrier island that fringes the Gulf of Mexico (Figure 1-1). The U.S. Department of Defense Readiness and Environmental Protection Integration Program aims to design and permit three specific nature-based solutions projects as part of Tyndall's layered coastal defenses. The three nature-based solutions projects include an Oyster Reef Breakwater site, a Living Shoreline site, and Submerged Shoreline Stabilization site, all of which are shown on Figure 1-1.

The present study is a follow-up to the previously completed 60% design stage for calibrated models (Jacobs 2023), which completed the calibration of the hydrodynamic (HD) and wave models and applied them to determine the design operational and extreme conditions for the existing conditions (baseline scenario). The present study is the second modeling phase at the 60% design stage; it builds on the previous study by focusing on the following tasks:

- Provide sediment data as inputs to the sediment transport modeling via additional data collection, review, and analysis.
- Use preferred layouts details to update the model mesh for simulations of the proposed conditions.
- Apply calibrated models to assist in layout optioneering.
- Determine annual sedimentation rates and the associated impacts relative to the existing condition via annual sediment transport modeling of the preferred layouts at the three sites.
- Apply the calibrated models to determine extreme flows and waves associated with the preferred layouts.

The modeling adopts a tiered approach, as illustrated on Figure 1-2.

Figure 1-1. Location of the Proposed Nature-based Resilience Projects

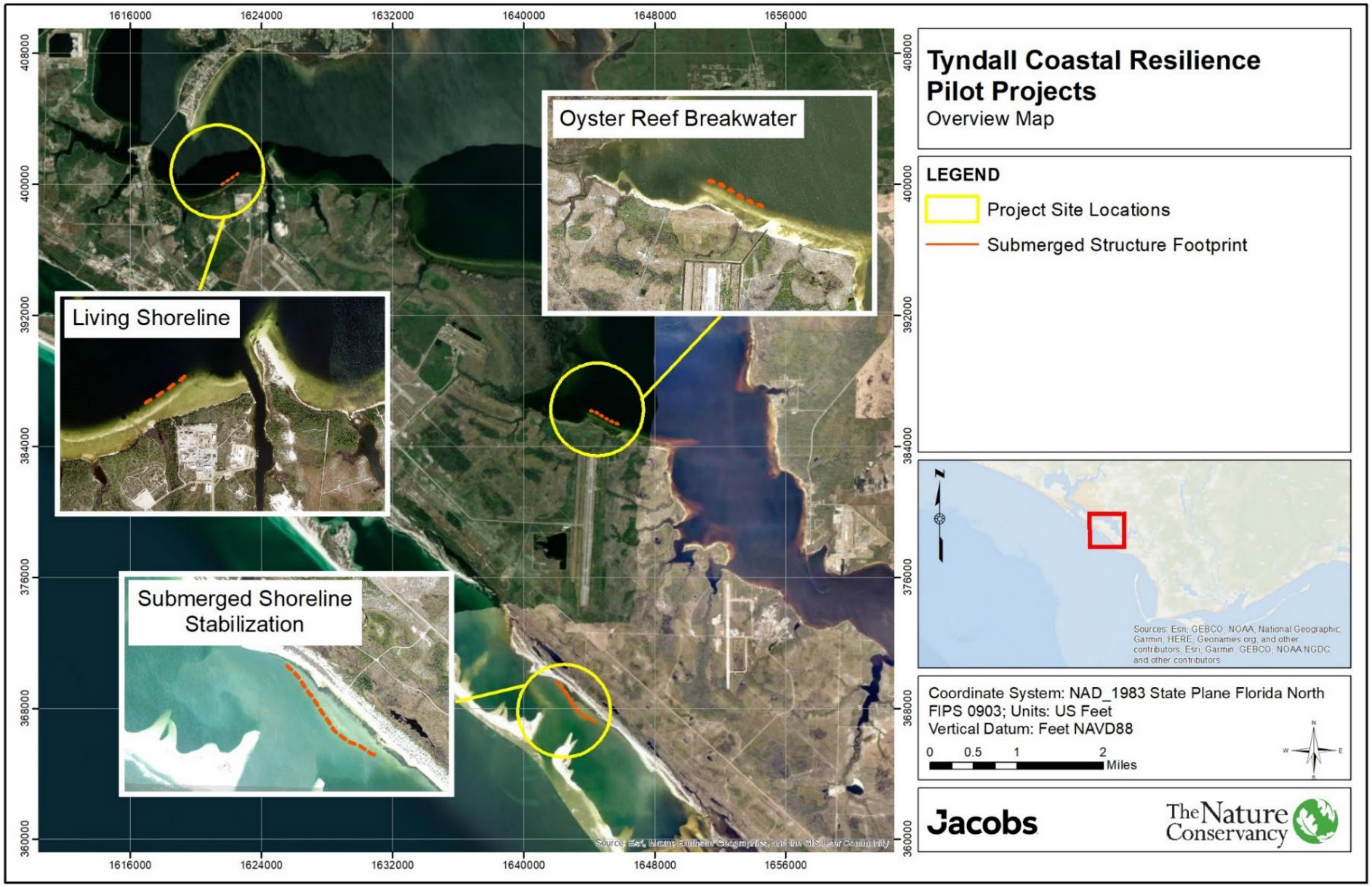
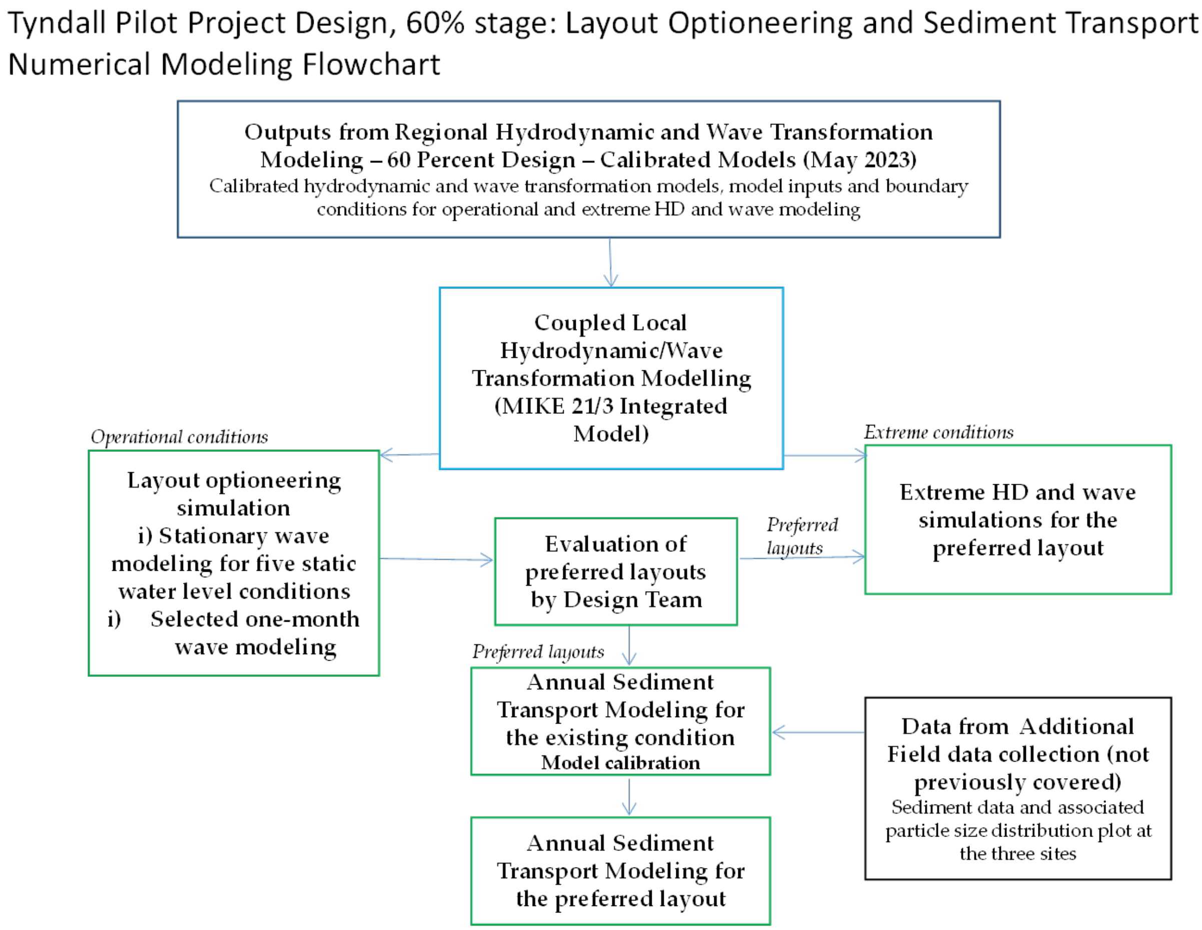


Figure 1-2. 60% Modeling Flow Chart Showing the Linkages Between Tasks



This report describes the process of the numerical modeling and the resulting findings at the following three project sites: the Submerged Shoreline Stabilization site (coastal site), the Oyster Reef Breakwater site (East Bay site), and the Living Shoreline site (East Bay site) around Tyndall AFB (Figure 1-1).

A newer version of the Danish Hydraulic Institute software package MIKE 21 (DHI 2024a, 2024b) was used to simulate the tidal level variation, current speed and direction, wave height, period, and direction at each project site. The details of numerical modeling are presented in the relevant sections that follow.

1.1 Report Organization

This report summarizes the application of the previously developed calibrated wave and hydrodynamic models for layout optioneering and the annual sediment transport modeling of the existing condition and preferred layouts at Tyndall AFB. The report is structured as follows:

- Section 2 presents the additional data sources and analyses.
- Section 3 discusses the assessment of historical sedimentation.
- Section 4 examines the application of the calibrated modeled in annual sediment transport modeling of the existing conditions (baseline).
- Section 5 analyzes the application of the calibrated models in layout optioneering.

- Section 6 presents the application of the calibrated models in annual sediment transport modeling of the preferred layouts.
- Section 7 discusses the application of the calibrated models to determine extreme flows and waves for the preferred layouts.
- Section 8 provides conclusions and recommendations.

2. Additional Data Source and Analysis

Available data are discussed in a previous report (Jacobs 2023) and are not repeated herein for brevity. The only new data relates to the preferred layouts presented in Section 2.2 and seabed sediments that were collected via field data collection as presented in Section 2.3.

2.1 Coordinate Conventions

The coordinate conventions adopted for the study are as follows:

- Horizontal: World Geodetic System 1984 Universal Transverse Mercator zone 16 north (meters)
- Vertical: North American Datum of 1988 (NAVD 88) (meters)

2.2 Project Layouts

During the Preliminary Design Workshop on April 20, 2023, the Bird/Wildlife Aircraft Strike Hazard group raised concerns that structure segments might attract birds and endanger aircraft traffic at the base. After discussing the possible impacts in more detail, it was determined that the structure at all three project sites needs a crest elevation not higher than the current mean lower low water (MLLW). More detailed information can be obtained from the basis of design reports (Jacobs 2024a, 2024b, 2024c). Table 2-1 lists a summary of the project layout characteristics.

Table 2-1. Layout Parameters for Each Project Site

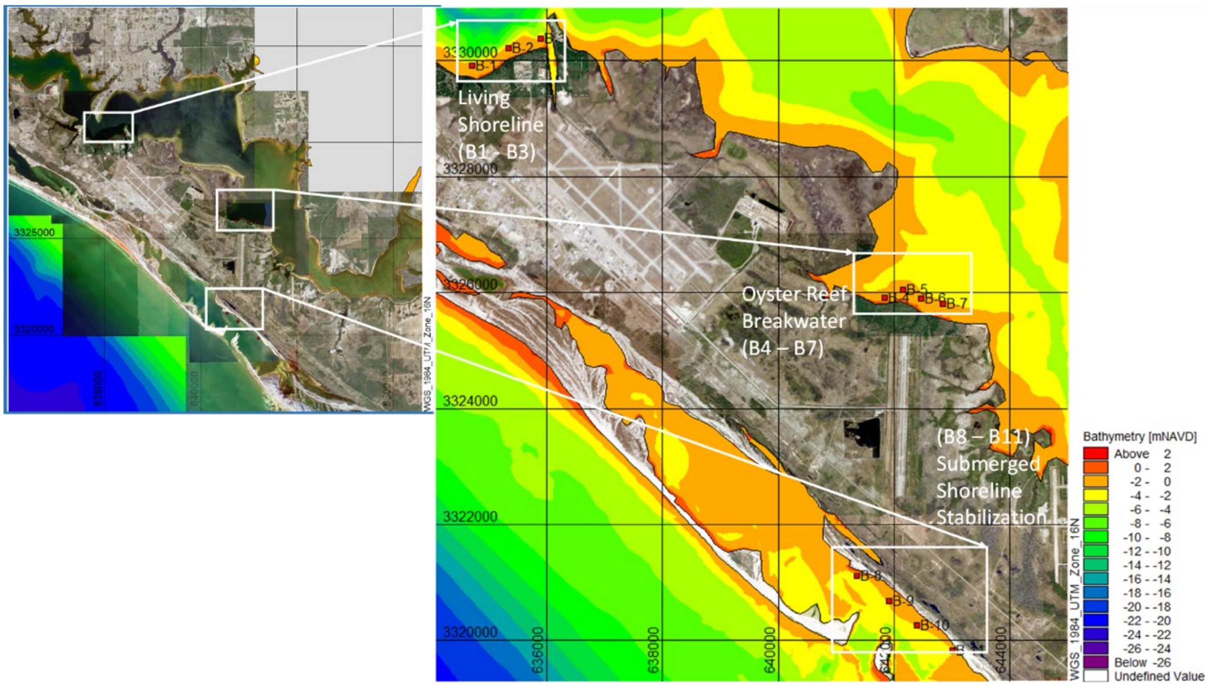
Pilot Project Site	Number of Structure Segments	Length of Structure Segments	Number of Gaps	Gap Width	Type of Structure Geometry
Living Shoreline	4	200	3	150	Simple
Oyster Reef Breakwater	6	200	5	160	Complex
Submerged Shoreline Stabilization	12	200	11	100	Simple

2.3 Sediment Data

A geotechnical investigation conducted as part of the site data collection for the project provided relevant sediment data in the project vicinity as per the spatial distribution of these sediment samples shown on Figure 2-1. They comprise boreholes (per Table 2-2) that yielded soil data on subsoil profile, percent sediment size composition, and particle size distribution plots, as summarized on Figure 2-2. Refer to Appendix C for the full Geotechnical Data Report.

As shown on Figure 2-2, the average median sediment size (that is, sediment with a size and diameter at 50% passing) at all the three sites is in the sand size range. It is therefore considered appropriate to adopt sand-sized sediments to characterize the sedimentation regime in the project vicinity for the purpose of sedimentation modeling.

Figure 2-1. Distribution of Available Boreholes



Note: Distribution is denoted by the white rectangles.

Table 2-2. Location Details of Boreholes

Site	Borehole Identification	Longitude (°E)	Latitude (°N)	Depth to Mudline (m)
Living Shoreline	B-1	-85.601986	30.092978	4.5
	B-2	-85.595434	30.095694	4.5
	B-3	-85.589715	30.097072	4.5
Oyster Reef Breakwater	B-4	-85.528685	30.056108	4.0
	B-5	-85.525309	30.057245	4.0
	B-6	-85.522078	30.055912	4.5
	B-7	-85.518246	30.055046	5.5
Submerged Shoreline Stabilization	B-8	-85.534205	30.012856	7.5
	B-9	-85.528623	30.008872	6.5
	B-10	-85.523715	30.005089	8.5
	B-11	-85.517378	30.001044	9.0

° = degree(s)
E = east
N = north
m = meter(s)

Figure 2-2. Summary of the Results by the Geotechnical Analysis

BH ID	Site	Sample depth	Sediment size (mm)			Geometrical Spreading	Specific Gravity	Percentage Size		Site averaged	
			D84	D50	D16			Sand	Silt & Clay	D50	GS
B-1	Living Shoreline	0-1.5	0.32	0.21	0.18	1.33		100	0	0.21	1.30
		2-3.5	0.34	0.21	0.18	1.37	2.66				
		8-9.5	0.29	0.16	0.076	1.95					
B-2		2 - 3.5	0.3	0.22	0.18	1.29		99	1		
B-3		0-1.5	0.29	0.2	0.18	1.27		99	1		
B-4	Oyster Reef Breakwater	0-1.5	0.35	0.22	0.18	1.39		98	2	0.21	4.22
		2-3.5	0.36	0.2	0.001	18.97	2.65				
		4-5.5	0.36	0.22	0.11	1.81					
		6-7.5	0.36	0.2	0.08	2.12					
B-5		0-1.5	0.35	0.21	0.14	1.58		100	0		
		4-5.5	0.4	0.22	0.08	2.24					
		8-9.5	0.38	0.18	N.A.						
B-6		0-1.5	0.36	0.22	0.18	1.41		100	0		
		4-5.5	0.34	0.21	0.16	1.46					
		8-9.5	0.45	0.25	0.15	1.73					
B-7		6-7.5	0.35	0.22	0.12	1.71					
		10-11.5	0.05	N.A.	N.A.		2.60				
B-8	Submerged Shoreline Stabilization	0-1.5	0.34	0.21	0.18	1.37				0.22	1.40
B-9		4 - 4.5	0.35	0.21	0.17	1.43	2.62	98	2		
B-10		0-1.5	0.34	0.21	0.18	1.37		99	1		
B-11		0-1.5	0.37	0.23	0.18	1.43		99	1		

Notes: BH = BoreHole; N.A. = Not Available, D84 = grain size 84% finer by weight; D50 = grainsize 50% finer by weight (medium); D16 = grain size 16% finer by weight; GS = $(D84/D16)^{0.5}$

3. Analysis of Historical Sedimentation

The various bathymetric surveys over the years constitute a record of the actual sedimentation in the project vicinity. Understanding the historical sedimentation pattern was achieved by examining the bathymetric changes from time-separated bathymetry surveys.

3.1 Panama 2010 Digital Elevation Model

The bathymetric data is extracted from National Oceanic and Atmospheric Administration (NOAA) Panama City 2010 data in NAVD 88, with units in meters (that is, the Panama City, Florida, 1/3 arc-second NAVD 88 Coastal Digital Elevation Model). This model was developed by NOAA's National Centers for Environmental Information (NCEI). The data points are arranged in a regular and approximately square grid with a nominal uniform grid size of 9 meters by 10 meters.

The data covers the topography of the project vicinity. The original data points were arranged in a regular square grid with a uniform grid size of 1 meter and have been resampled to a coarser grid of 10 meters for use.

NOAA's NCEI is developing a suite of digital elevation models (DEMs) for use along the U.S. coast. These DEMs seek to support a variety of NOAA missions, including improved inundation modeling and mapping, habitat characterization, and visualization of Earth's surface. The DEMs are being developed according to a 0.25° tiling scheme. The spatial resolution of the tiles (that is, telescopes) from the coastal zone to the deep ocean floor are at 1/9, 1/3, and 3 arc-second grid resolution. Only the 1/9 arc-second DEM tiles integrate both bathymetric and topographic data; all other resolutions map bathymetry only. The tiling of the DEMs facilitates targeted and rapid updates as new coastal and marine elevation data are acquired and become available. Bathymetric and topographic data used for DEM creation originate from a variety of sources, including, but not limited to, the NOAA Office of Coast Survey, NOAA National Geodetic Survey, NOAA Office for Coastal Management, U.S. Geological Survey, and the U.S. Army Corps of Engineers. The topo-bathymetric data are archived for public access online (NCEI 2023).

3.2 Site Survey 2022

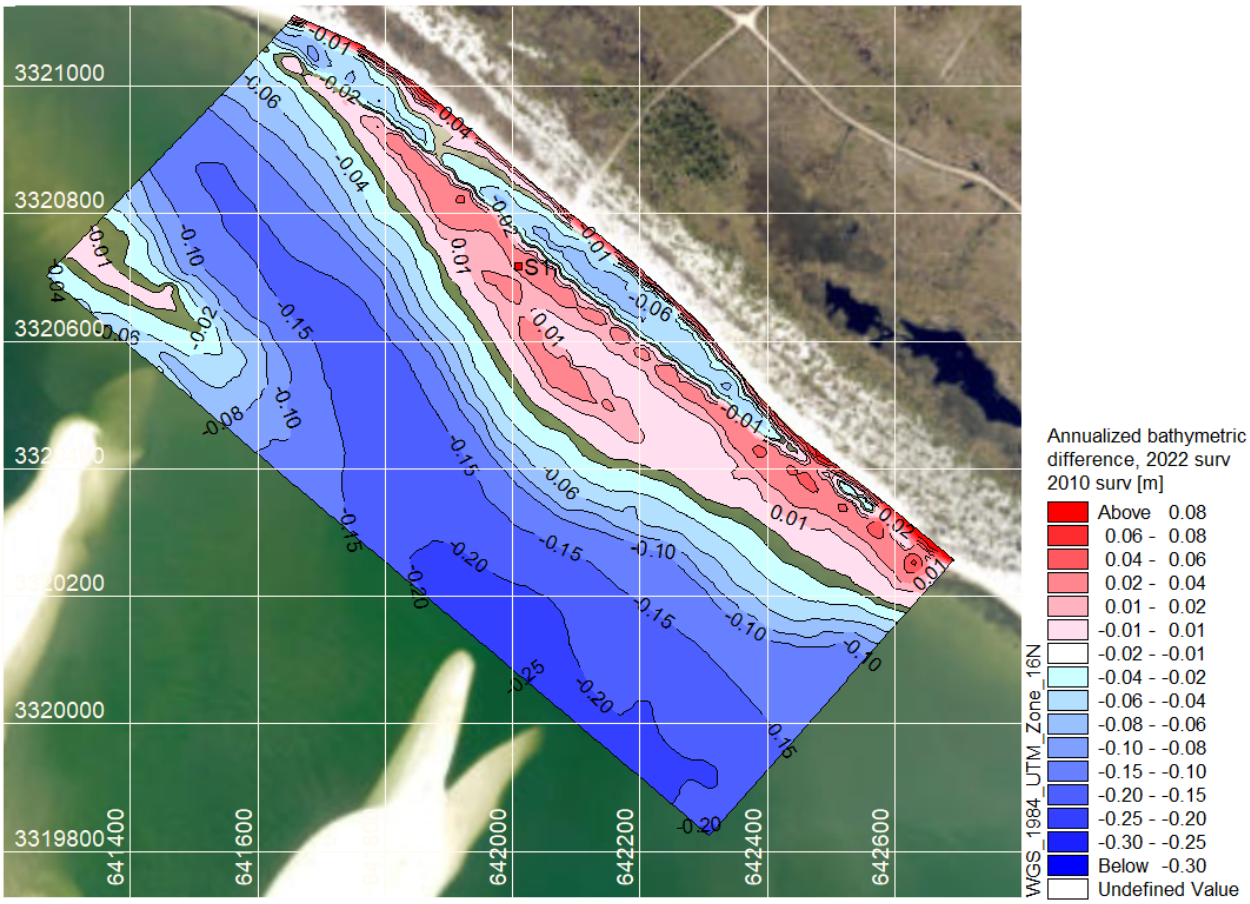
In addition to the topo-bathymetric data used in the 30% stage, a recent site bathymetric survey covering the three sites was completed in November 2022 (Ruben Surveying and Mapping 2023).

First, the overlapping areas of the two surveys were determined. Next, the historical sedimentation depth within the overlapping areas was computed as the difference in bathymetric depths as noted in the previously referenced surveys, which covered a 12-year period. The annualized sedimentation rate (meters per year) was then computed based on linear scaling as total bathymetric difference/time span (12 years). The resulting distribution of the annualized sedimentation rates for the three sites is shown on Figure 3-1 through Figure 3-3.

- Submerged Shoreline Stabilization: Figure 3-1 displays two broad shoreline parallel bands of alternating sedimentation nearshore at an average annual rate of 0.02 meter and erosion further seaward at an average rate of -0.1 meter.
- Oyster Reef Breakwater: Figure 3-2 displays a trend toward slight depositional at an average rate of 0.02 meter.
- Living Shoreline: Figure 3-3 displays a trend toward deposition at an average higher rate of 0.05 meter but interspersed with pockets of erosion area at an average rate of 0.03 meter.

These figures were then used as the basis to adjust and tweak the model settings and values of the sedimentation model to match with modeled annual sedimentation depths for the existing conditions. Once considered calibrated, the model was then applied to the proposed layouts to predict the future sedimentation regime resulting from the proposed works.

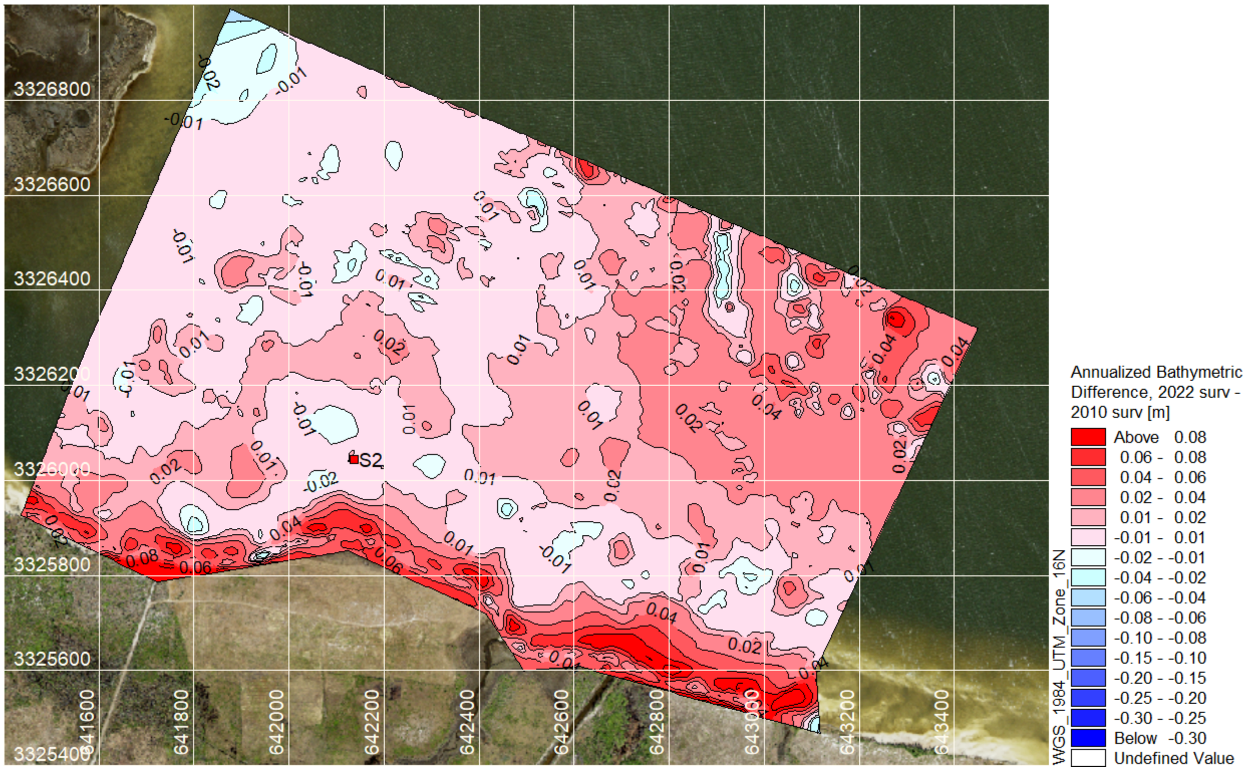
Figure 3-1. Annualized Bathymetric Difference from 2010 to 2022 within the Survey Overlapped Area: Submerged Shoreline Stabilization Site



Note: Red color denotes sedimentation; blue denotes erosion.

Surv = survey

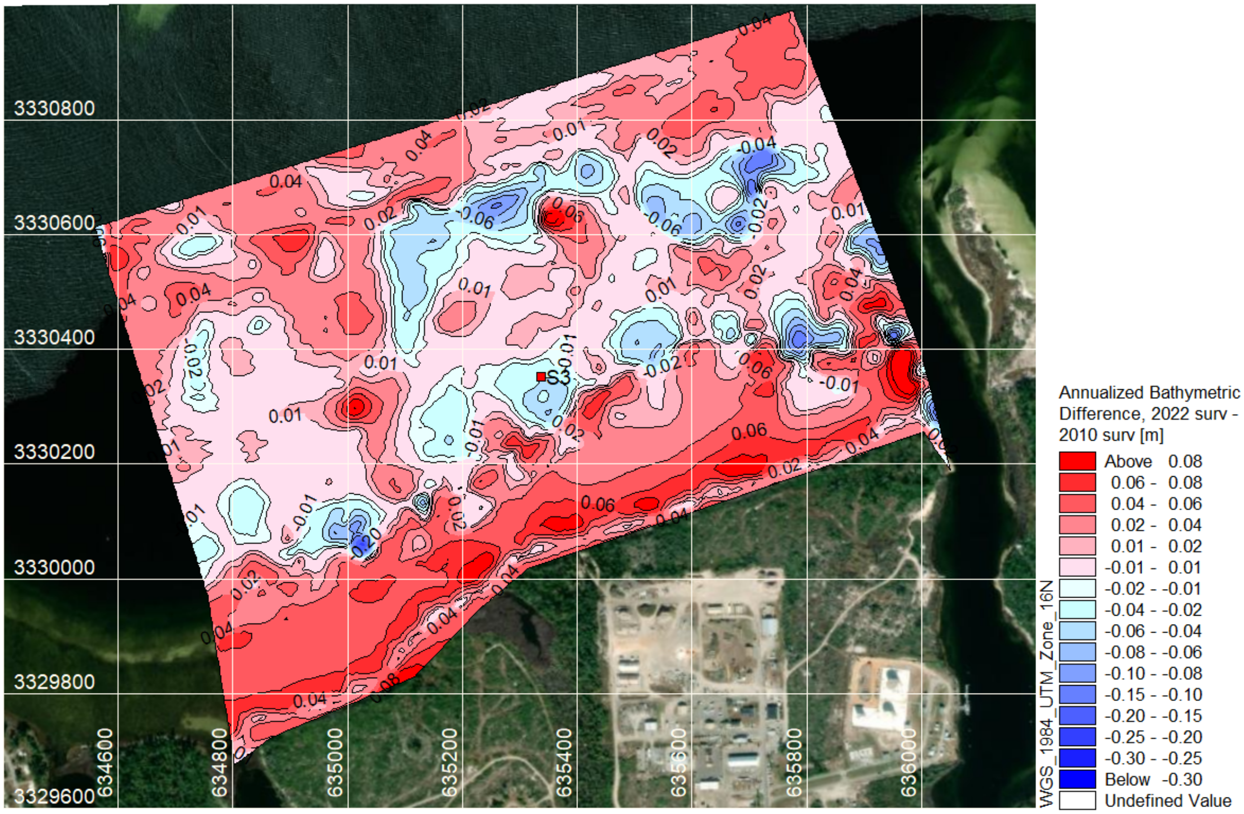
Figure 3-2. Annualized Bathymetric Difference from 2010 to 2022 within the Survey Overlapped Area: Oyster Reef Breakwater Site



Note: Red color denotes sedimentation; blue denotes erosion.

Surv = survey

Figure 3-3. Annualized Bathymetric Difference from 2010 to 2022 within the Survey Overlapped Area: Living Shoreline Site



Note: Red color denotes sedimentation; blue denotes erosion.

Surv = survey

4. Annual Sediment Transport Modeling, Existing Condition

This section describes the methodology, tasks, and results of the annual sediment transport modeling.

4.1 Modeling Methodology and Tasks

The modeling methodology is outlined as follows:

- Collect site sediment data and their analysis to yield sediment-related inputs for use.
- Develop an area-wide sediment transport model using the results of the hydraulic and wave transformation modeling.
- Conduct a 1-year (2022) run of coupled HD and wave modeling using the calibrated parameters from Jacobs (2024).
- Apply the previously listed methodology as drivers to conduct sediment transport modeling under operational conditions including seasonal changes for the base condition.
- Calibrate the sediment transport model by comparing with historical sedimentation derived in Section 3.
- Assess the annual sedimentation rates in the project vicinity.

The modeling tasks proceeded as follows:

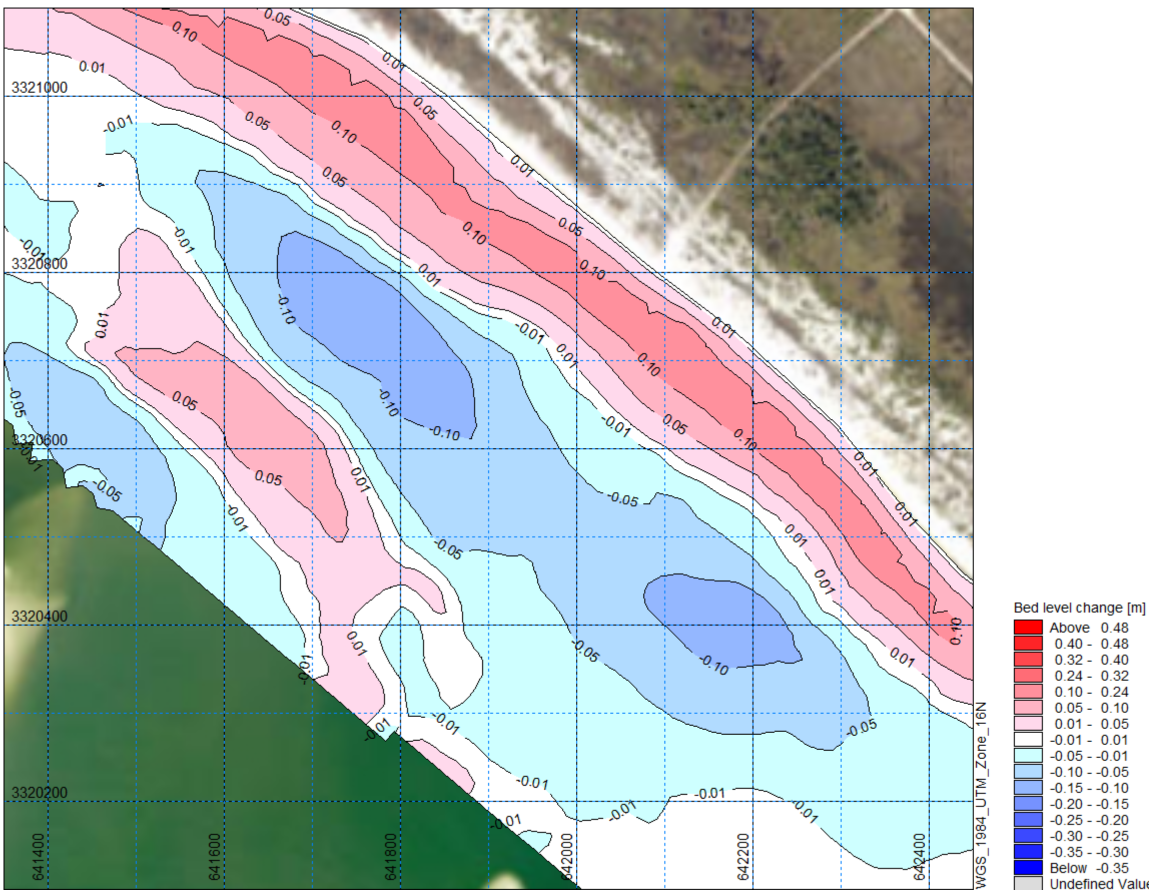
- The annual period for simulation was selected. In this case, the year that includes the calibration period (August 2, 2022, to October 19, 2022, which coincided with the period of Acoustic Doppler Current Profiler measurement) was selected by extending it to cover the entire year (that is, from January 1, 2022, to December 31, 2022).
- For time efficiency, the annual model, simulation period was split up into six bi-monthlysegments that ran on several modeling machines in parallel.
- The coupled HD and wave simulations were first conducted, and the resulting individual decoupled HD solution files that consisted of the flux and flow outputs were then concatenated to provide continuous time series area outputs that stretched across the entire year.
- Similarly, the resulting individual wave fields were concatenated to provide a continuous time series area output that stretched across the entire year.
- Sediment transport tables that cover the ranges of wave height, wave period, median sediment diameter, geometrical spreading current speed, and bed slopes in two orthogonal directions were generated using the Generation of Quasi-3D Sediment Tables utility available in the MIKE 21 Toolbox (DHI 2024d). It was based on Bowen and Doering's wave theory (Bowen and Doering 1995), making it applicable for all depths.
- The assembled 1-year decoupled HD files were then applied to drive the sediment transport model where the assembled 1-year wave fields were specified as an external input.
- Model inputs include median sediment size and geometrical spreading, both of which are based on the available sediment data discussed in Section 2. The only model parameter that was varied until the match between the historical annual sedimentation rates and the modeled annual sedimentation rates within the defined area of interest was deemed satisfactory, was the maximum bed level change rate per day.

4.2 Model Results

The outputs are presented in the form of spatial distribution of bed level change (annual sedimentation rate) over the entire model domain. The last time step of the outputs at the end of 2022 was used as the annual sedimentation rate to compare with the historical sedimentation rate maps discussed in Section 3.

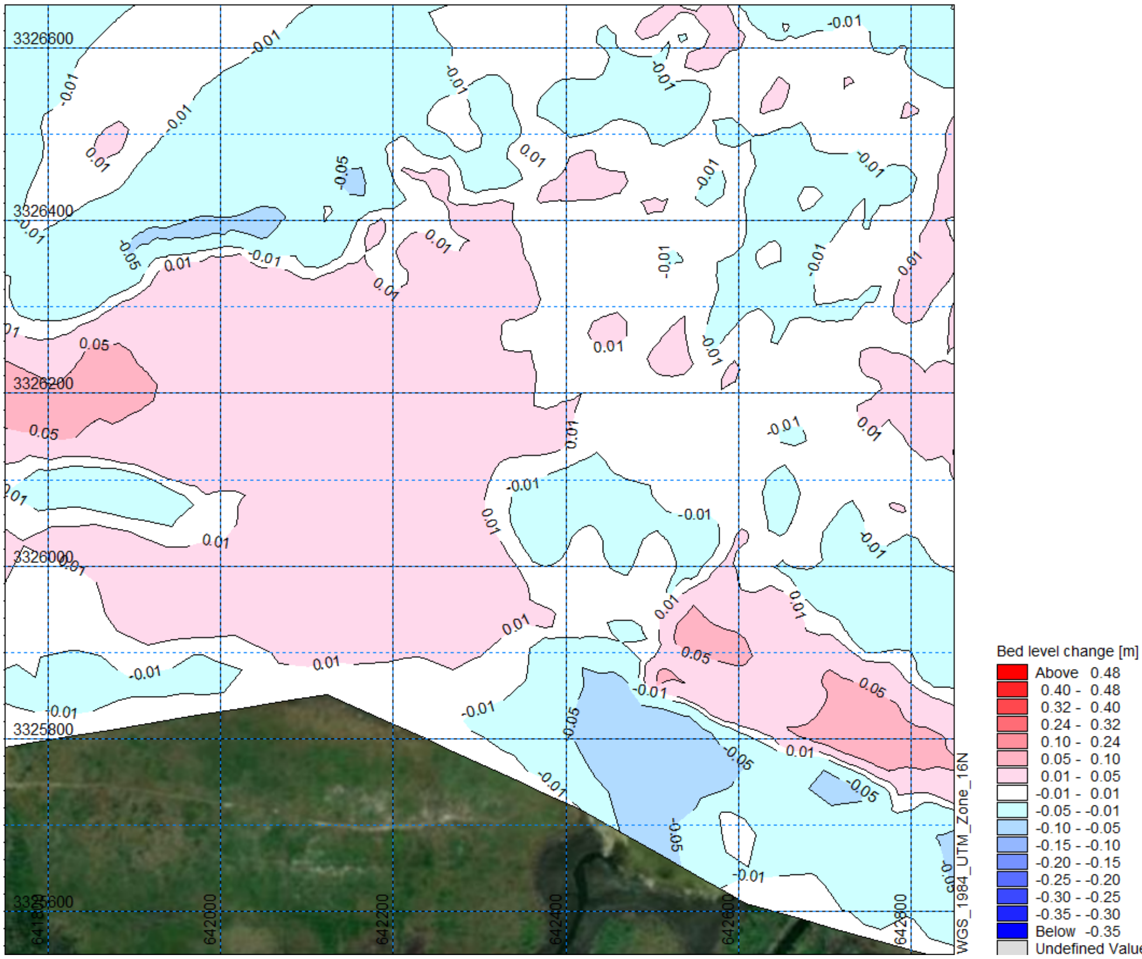
The modeled annual sedimentation rates that resulted from the application of a maximum bed level change rate of 0.005 meter per day were deemed satisfactory, as shown on Figures 41 through 43.

Figure 4-1. Modeled Distribution of Annual Sedimentation Rate for the Submerged Shoreline Stabilization Site in its Existing Condition



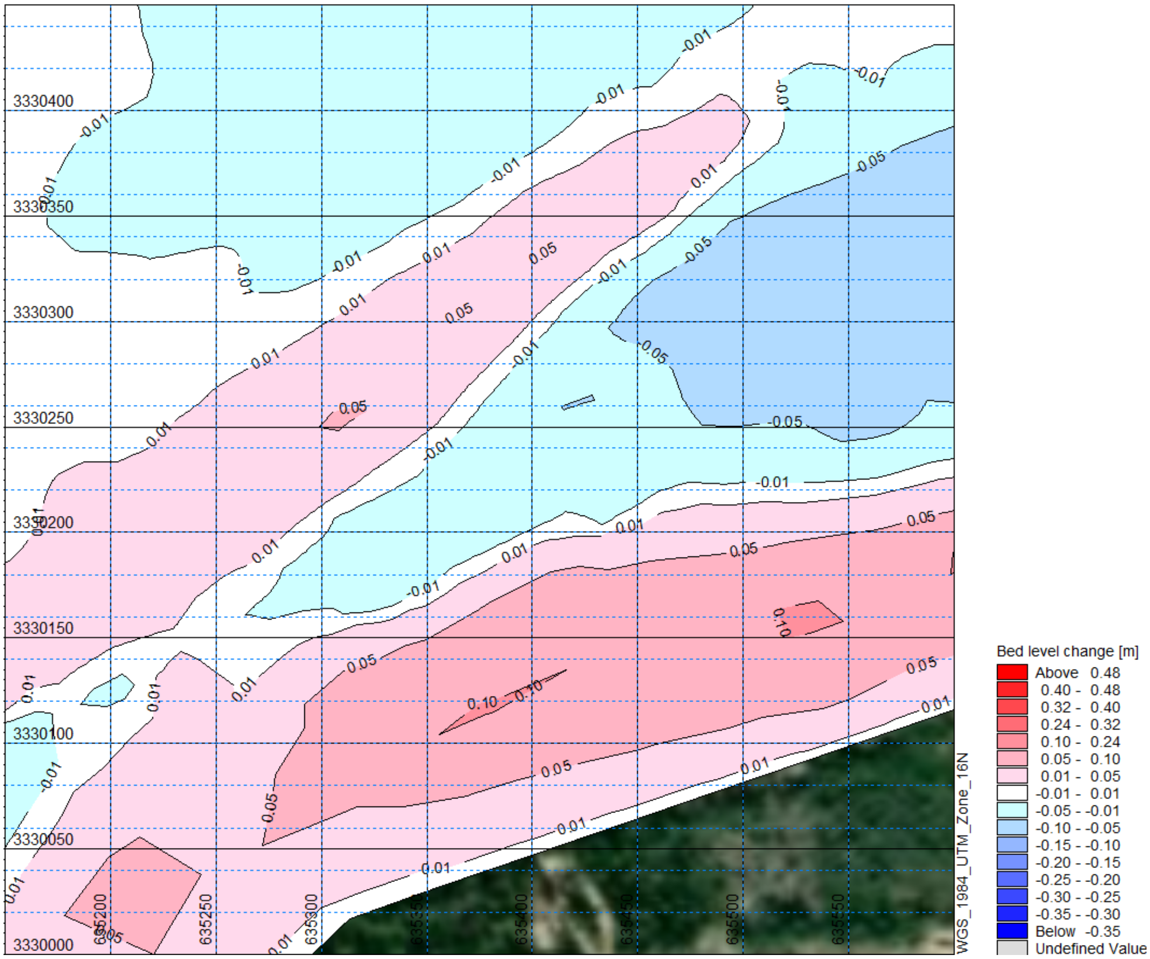
Note: Red color denotes sedimentation; blue denotes erosion.

Figure 4-2. Modeled Distribution of Annual Sedimentation Rate for the Oyster Reef Breakwater Site in its Existing Condition



Note: Red color denotes sedimentation; blue denotes erosion.

Figure 4-3. Modeled Distribution of Annual Sedimentation Rate for the Living Shoreline Site in its Existing Condition



Note: Red color denotes sedimentation; blue denotes erosion.

4.3 Caveats on the Model Results

The following subsections outline caveats to the model results.

4.3.1 Annual Historical Sedimentation Rates Derivation Accuracy

Of the two survey datasets used in the derivation, one was measured at the site with a known year and date of the survey. The second one was downloaded from the NCEI's archived topo-bathymetry website and did not indicate the actual date of the survey data used, except for their sources. The year of survey data used was assumed to be the same as the one in the data file name, the origin of which cannot be traced now. No other high-resolution survey conducted by a Professional Land Surveyor was available at the time the modeling was completed.

4.3.2 Dynamic Nature of the Entrance Bar to the Site

The present model results are based on a single opening and inlet through the entrance bar, which is consistent with the situation shown on Figure 4-4. The entrance bar, however, is highly dynamic and may exhibit the presence of another significant bar breach, as shown on the bottom image of Figure 4-4. At another time, a partial bar breach can be seen, as indicated in the middle image on Figure 4-4. A single or a double opening configuration in this context may have profound impact on the ambient hydraulic regime that drives sediment transport, which leads to uncertainty in the model results.

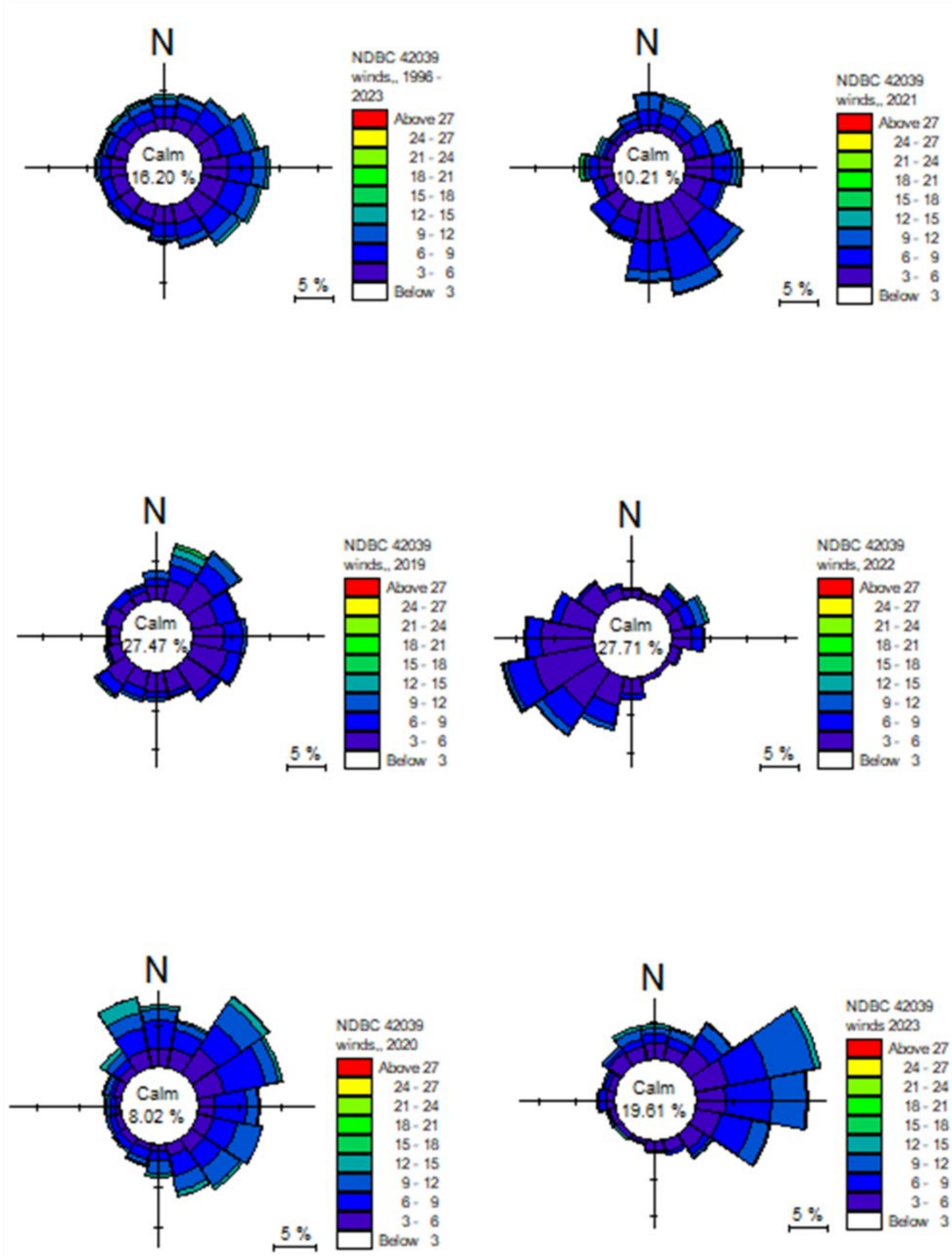
4.3.3 Interannual Variation in the Ambient Wind Climate

The ambient wind climate shows significant interannual variability (Figure 4-5). Wind is a major driver for flows and waves for all the three sites, but more so for the near-totally enclosed East Bay sites. To the extent that a multi-year simulation is not feasible because of budgetary and schedule constraints, selecting a representative year for modeling is difficult.

Figure 4-4. Temporal Evolution of the Entrance Bar to the Submerged Shoreline Stabilization Site

Note: Figure is based on aerial images taken at different times.

Figure 4-5. Comparison of Different Annual Wind Roses with Reference to the Average Annual Wind Rose



5. Design Optimization

This section describes the methodology, analysis, and results of the design optimization approach conducted

5.1 Modeling Purpose and Methodology

Design optimization was undertaken to find a balance between construction cost and structural functionality. As such, wave attenuation was analyzed to understand the impacts of reducing the number of segments and increasing the gap width between the segments for all three sites.

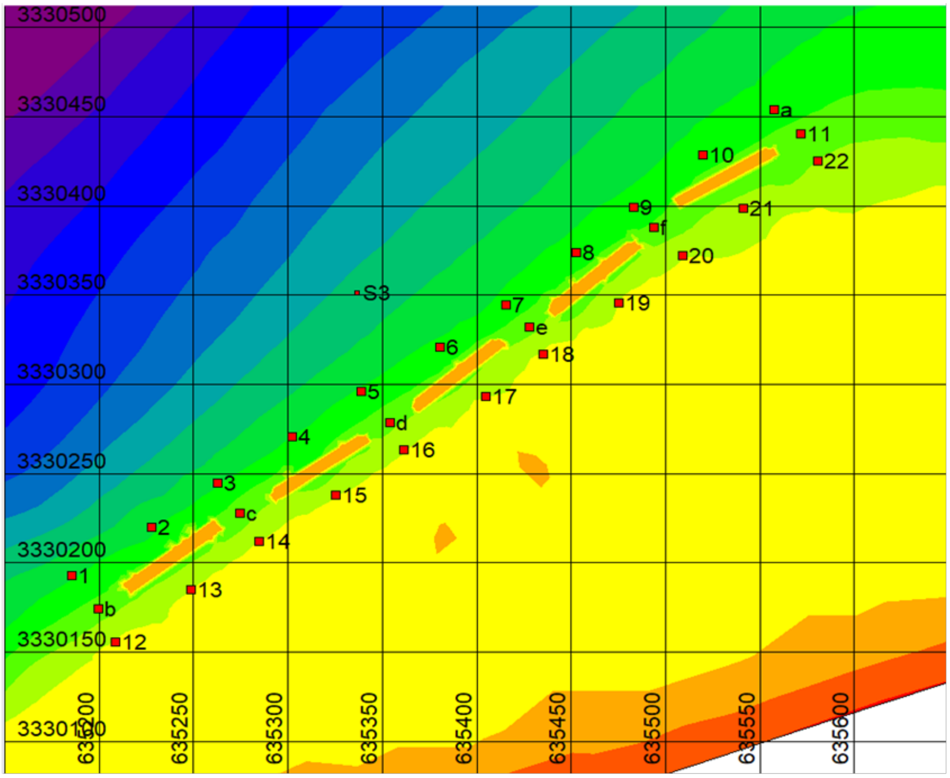
Wave attenuation of different layout schemes was investigated via quasi-stationary wave modeling where the crest elevation of the detached breakwaters is set at MLLW, which implies that the breakwater will be submerged below the water surface to varying degrees most of the time. Such a design leads to less design wave load and the use of less construction material, which contributes to cost savings. At the same time, higher waves will also be experienced in the lee. The impact of these potentially higher waves was investigated.

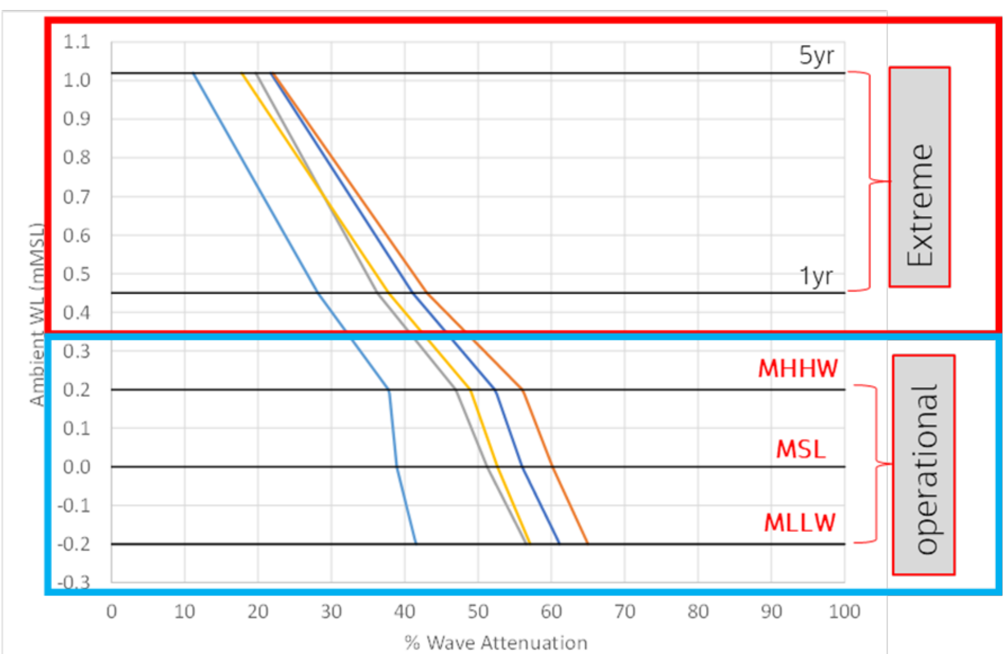
Wave modeling was conducted at various uniform water level stages that cover both operational conditions (MLLW to mean higher high water [MHHW]) and extreme conditions (1-and 5-year return period storms) to evaluate the percentage wave height attenuation of both the existing and proposed layouts.

5.2 Wave Attenuation Analysis Directly Behind Structures

The pairs of points of analysis were located approximately 30 feet seaward and landward of the breakwater trunk, thus forming transects. The resulting change in wave height along the various transects is shown on Figure 5-1 for the Living Shoreline site. Wave attenuation (that is, wave height reduction) is measured as a percent change between the wave heights at the landward point (17) and the seaward point (6), as shown in the lower plot on Figure 5-1. It is seen that increased water levels (wave heights over the structure crest) decrease wave attenuation across all transects (that is, larger waves at the landward side of the structures).

Figure 5-1. Location of Wave Evaluation Transects and Percent Wave Attenuation Variation with Ambient Water Levels along the Transects at the Living Shoreline Site



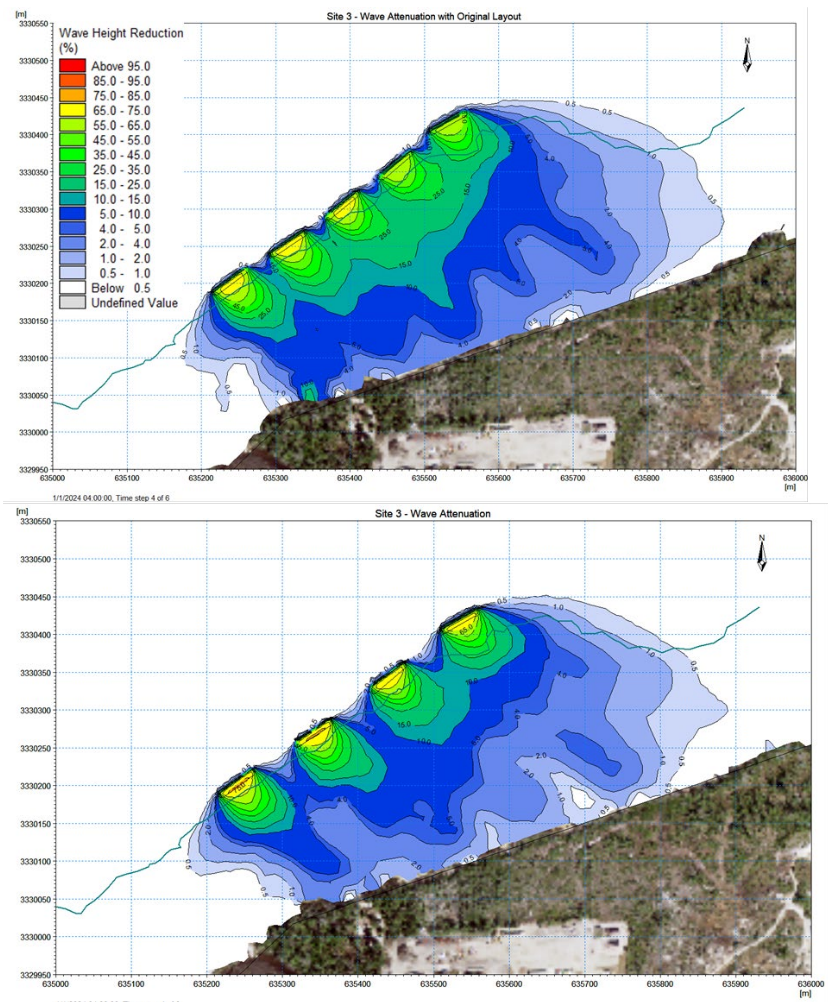


5.3 Area-Wide Wave Attenuation Analysis

For more complete coverage, the wave attenuation analysis at a single pair of points, as described in Section 5.2, was expanded to one spatial extent. This was conducted to account for spatial variability in the wave attenuation due to different structure gaps and to better serve as a basis for comparing different layouts. Figure 5-2 compares the extent of the spatial extent of wave attenuation for using the Living Shoreline site for two breakwater gap widths. The following observations can be made from Figure 5-2:

- A smaller (100-foot) gap allows smaller wave penetration (higher wave attenuation) through the gaps.
- The combined action of the multiple gaps with a smaller (100-foot) gap leads to an overall larger area of higher wave attenuation (dark green and dark blue) into the submerged aquatic vegetation (SAV) area behind the structures, resulting in less wave disturbance.

Figure 5-2. Spatial Extent Comparison of Wave Attenuation with Ambient Water Levels at the Living Shoreline Site



Notes:

Top: Five structures with 100-foot gaps.

Bottom: Four structures with 150-foot gaps

The continuous irregular light-blue line that is near-parallel to the shoreline denotes seaward edge of the SAV.

5.4 Results of Combined Attenuation Analysis

The following subsections describe the results of combined attenuation analysis for the Living Shoreline site, the Oyster Reef Breakwater site, and the Submerged Shoreline Stabilization site.

5.4.1 Living Shoreline

The combined plot is shown on Figure 5-3 and indicates the following:

- The percentage wave attenuation varies from 55% to 65% during operational conditions.
- Increasing water levels (extreme conditions) will decrease the percentage wave attenuation to approximately 40% attenuation for a 1-year event and 20% attenuation for a 5-year event.
- For an incident wave height of 0.5 meter and at a higher water level (MHHW relative to MLLW by 0.4 meter), the combined action of the multiple gaps leads to a spatial encroachment of higher waves (low wave attenuation zone marked by blue and green) into the SAV area almost right up to the shoreline.

5.4.2 Oyster Reef Breakwater

The combined plot is shown on Figure 5-4 and indicates the following:

- The percentage of wave attenuation varies from 80% to 90% during operational conditions.
- Increasing water levels (extreme conditions) will decrease the percentage of wave attenuation to approximately 65% attenuation for a 1-year event and 20% attenuation for a 5-year event.
- For an incident wave height of 0.5 meter and at a higher water level (MHHW relative to MLLW by 0.4 meter), the combined action of the multiple gaps leads to an overall spatial encroachment of higher waves (low wave attenuation zone marked by blue and green) into the SAV area that reaches the shoreline.

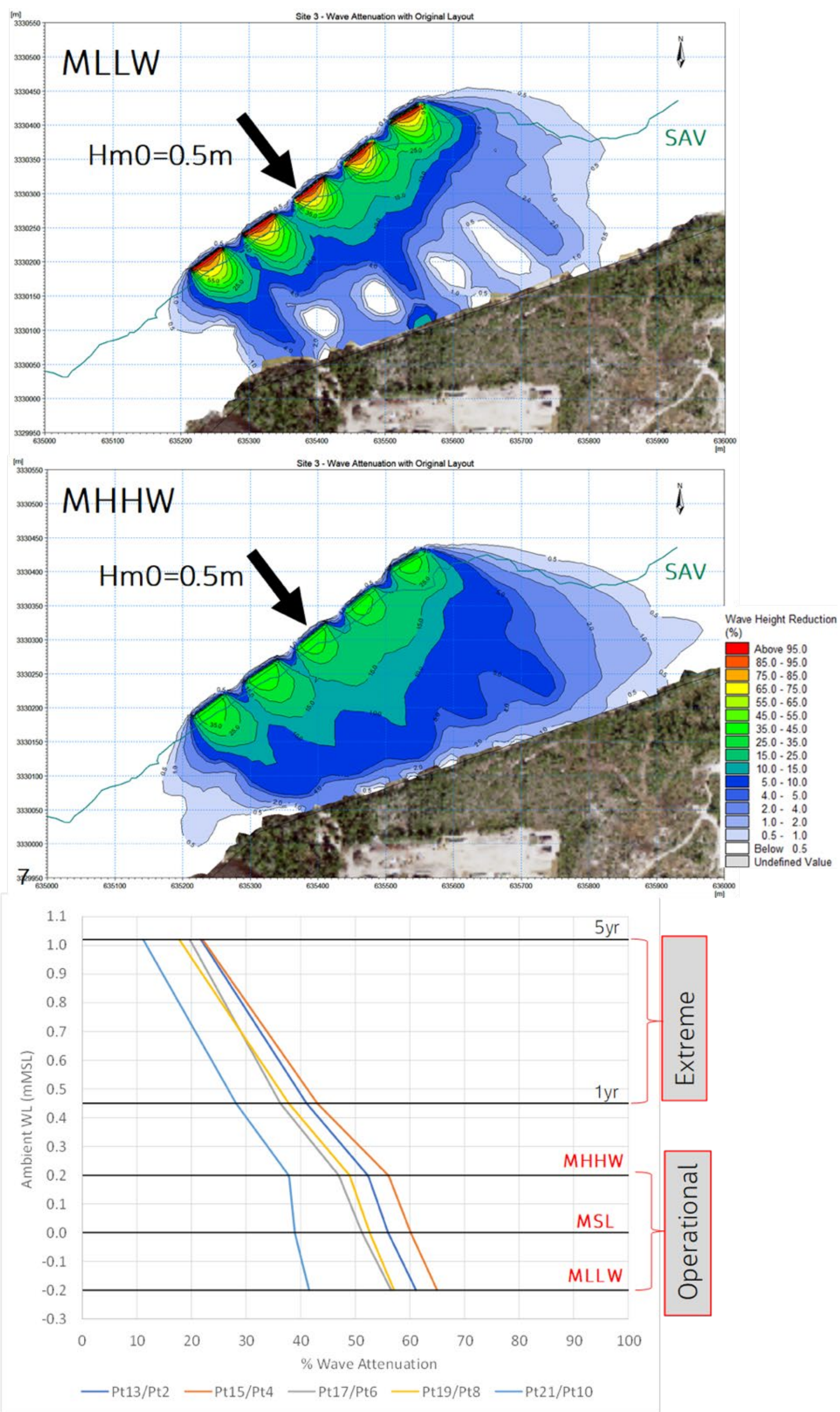
5.4.3 Submerged Shoreline Stabilization

The combined plot is shown on Figure 5-5 and indicates the following:

- The percentage of wave attenuation varies from 60% to 80% during operational conditions.
- Increasing water levels (extreme conditions) will decrease the percentage of wave attenuation to approximately 45% attenuation for a 1-year event and15% attenuation for a 5-year event.
- For an incident wave height of 0.6 meter and at a higher water level (MHHW relative to MLLW by 0.4 meter), the combined action of the multiple gaps leads to an overall spatial encroachment of higher waves (low wave attenuation zone marked by blue and green) into the SAV area that reaches the shoreline.

The wave attention analysis is a function of different layout and water level variations, which were fed to the design team as one of the inputs during design optimization. The preferred layouts for each site were applied in sediment transport modeling (Section 6) and extreme flow and wave modeling (Section 8).

Figure 5-3. Combined Wave Attenuation Plots at the Living Shoreline Site

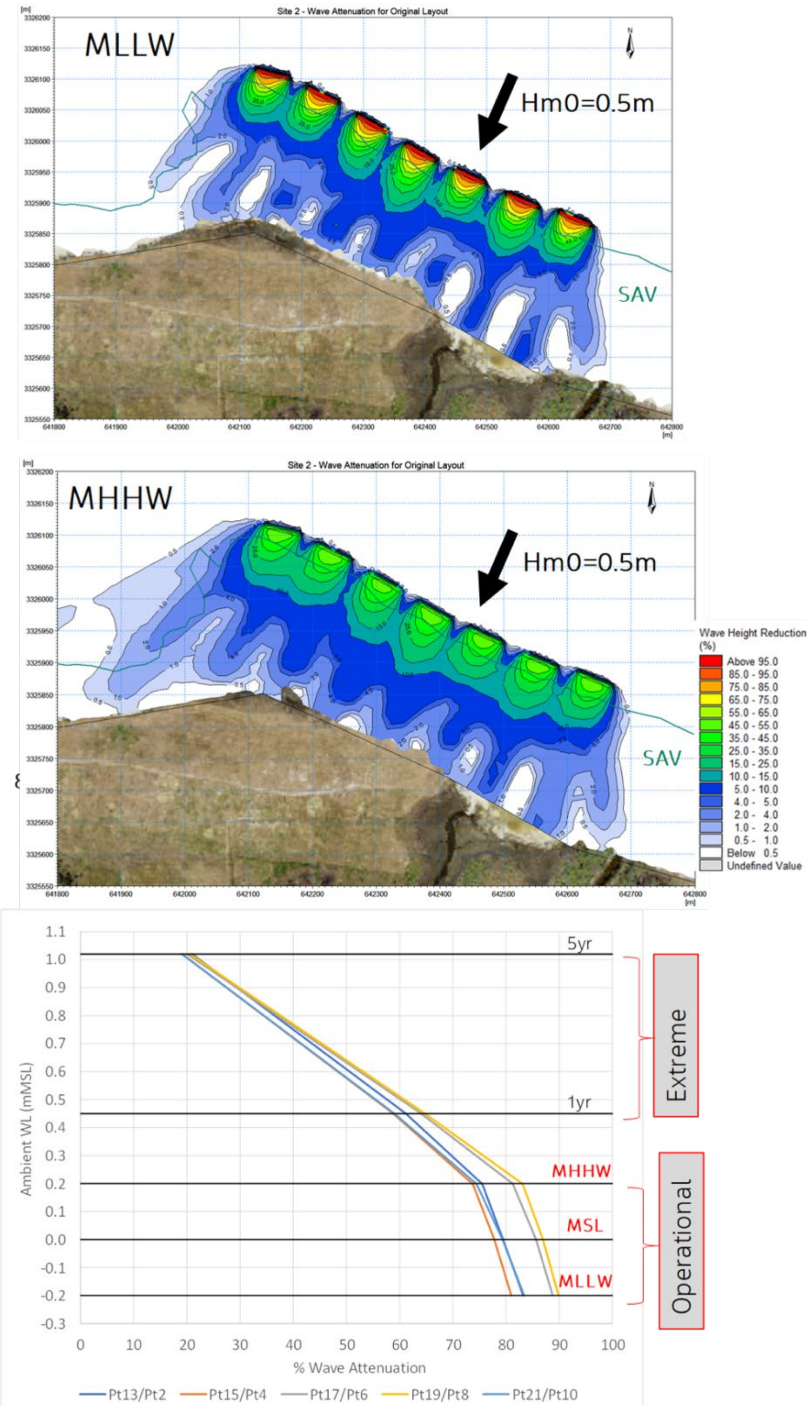


Notes:

Top: Spatial distribution of percent wave attenuation.

Bottom: Variation of percent wave attenuation with ambient water levels by transect locations.

Figure 5-4. Combined Wave Attenuation Plots at the Oyster Reef Breakwater Site

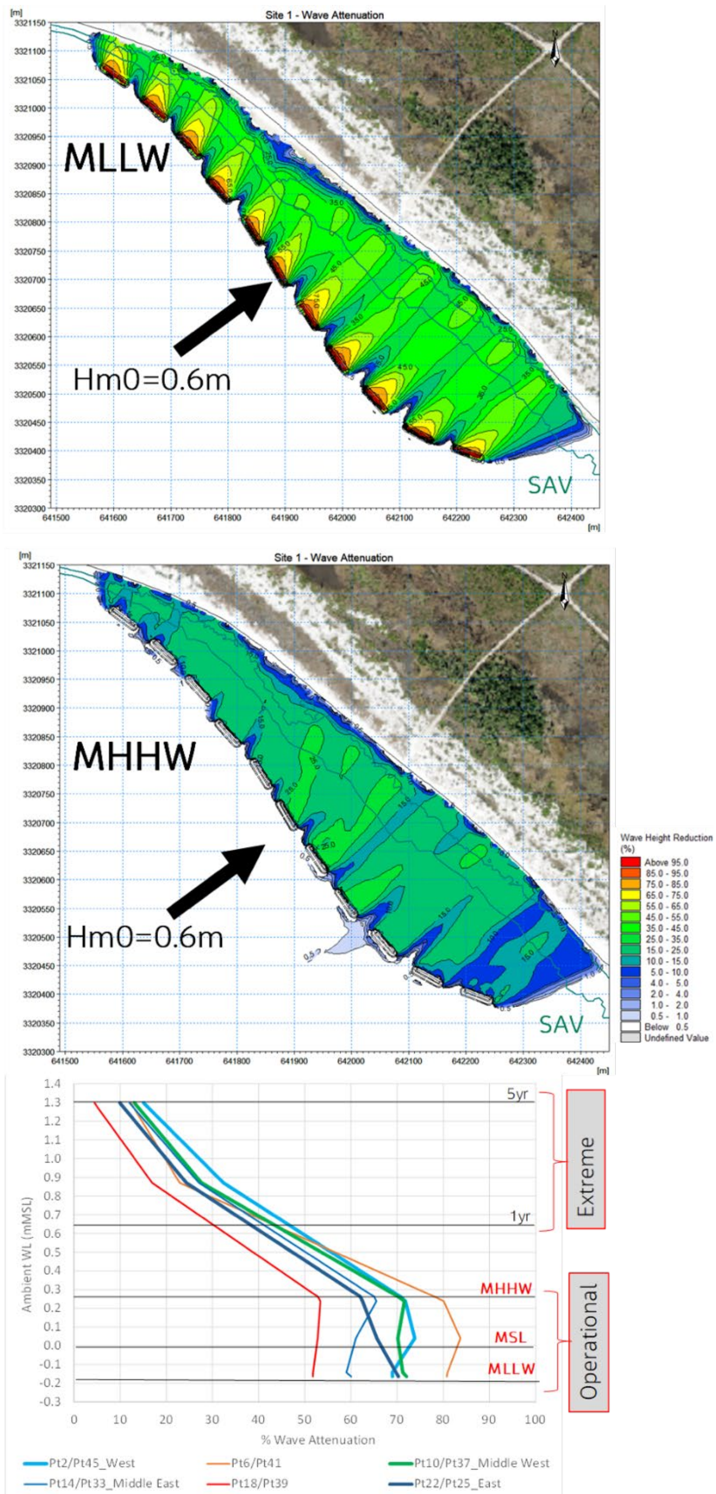


Notes:

Top: Spatial distribution of percent wave attenuation.

Bottom: Variation of percent wave attenuation with ambient water levels by transect locations.

Figure 5-5. Combined Wave Attenuation Plots at the Submerged Shoreline Stabilization Site



Notes:

Top: Spatial distribution of percent wave attenuation.

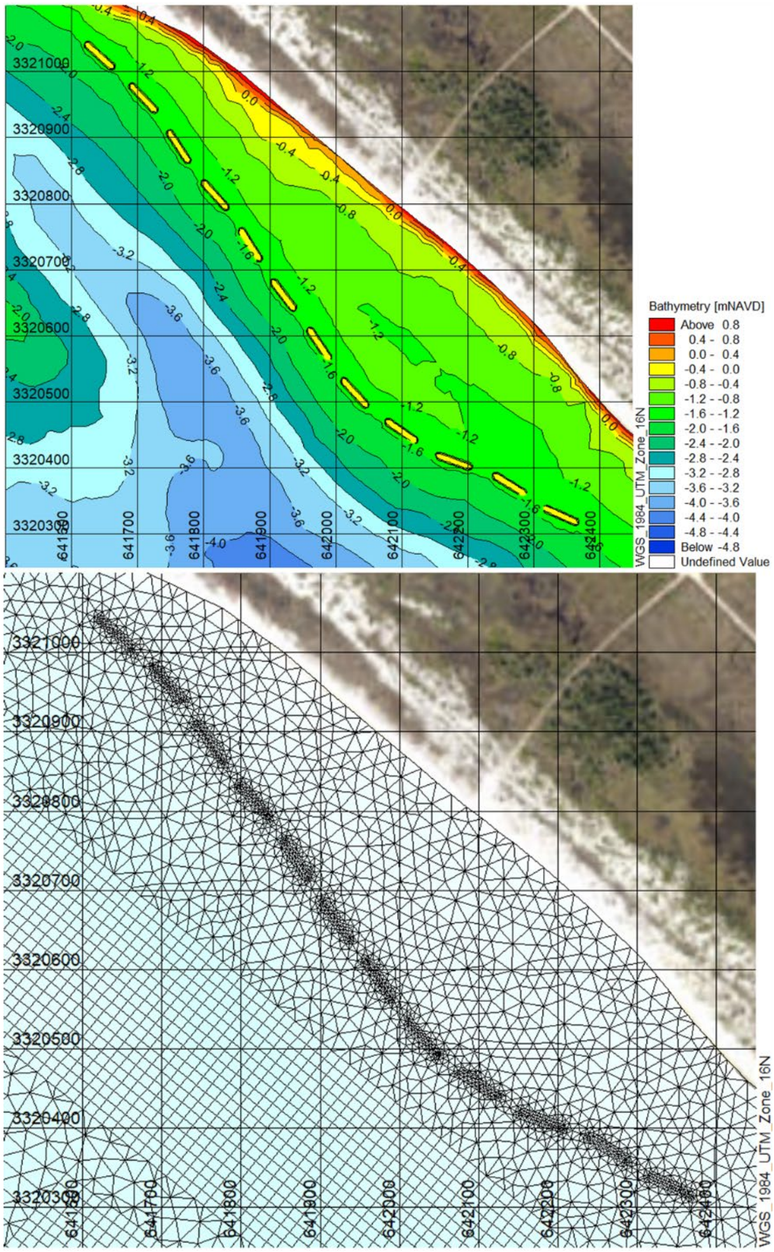
Bottom: Variation of percent wave attenuation with ambient water levels by transect locations.

6. Annual Sediment Transport Modeling – Preferred Layouts

The same modeling sequence outlined in Section 4 was applied herein, with the following exceptions:

- The model mesh was replaced by those incorporating the preferred layouts, comprising a series of detached breakwaters received from the design team at the end of their design optimization task. These preferred layouts are as follows:
  - **Submerged Shoreline Stabilization:** 12 segments of 200-foot-long straight submerged breakwaters spaced uniformly 100 feet apart along a curvilinear alignment, as shown on Figure 6-1 (upper plot). The total number of mesh nodes and mesh elements are 23,824 and 42, 631, respectively. The mesh distribution in the project vicinity is shown on Figure 6-1's lower plot.
  - **Oyster Reef Breakwater:** Six segments of 200-foot-long curvilinear submerged breakwaters spaced uniformly 150 feet apart along a nearly straight alignment where the leeward side consists of a series of finger spurs flanked by precast Defense Advanced Research Projects Agency (DARPA) units, as shown on Figure 6-2 (upper plot). The total number of mesh nodes and mesh elements are 31,192 and 53,060, respectively. The increased mesh resolution is a result of the smaller finger spurs and DARPA units at the Oyster Reef Breakwater site to resolve their smaller dimensions. The mesh distribution in the project vicinity is shown on Figure 6-2's lower plot.
  - **Living Shoreline:** Four segments of 200-foot-long straight submerged breakwaters spaced uniformly 150 feet apart along a shore parallel straight alignment as shown on Figure 6-3 (upper plot). The distribution of nodes and meshes is the same as those for the Oyster Reef Breakwater site, as the same mesh was used because of their proximity to each other (in the same bay area). The mesh distribution in the project vicinity is shown on Figure 6-3's lower plot.

Figure 6-1. Mesh Bathymetry and Resolution in the Submerged Shoreline Stabilization Site's Project Vicinity

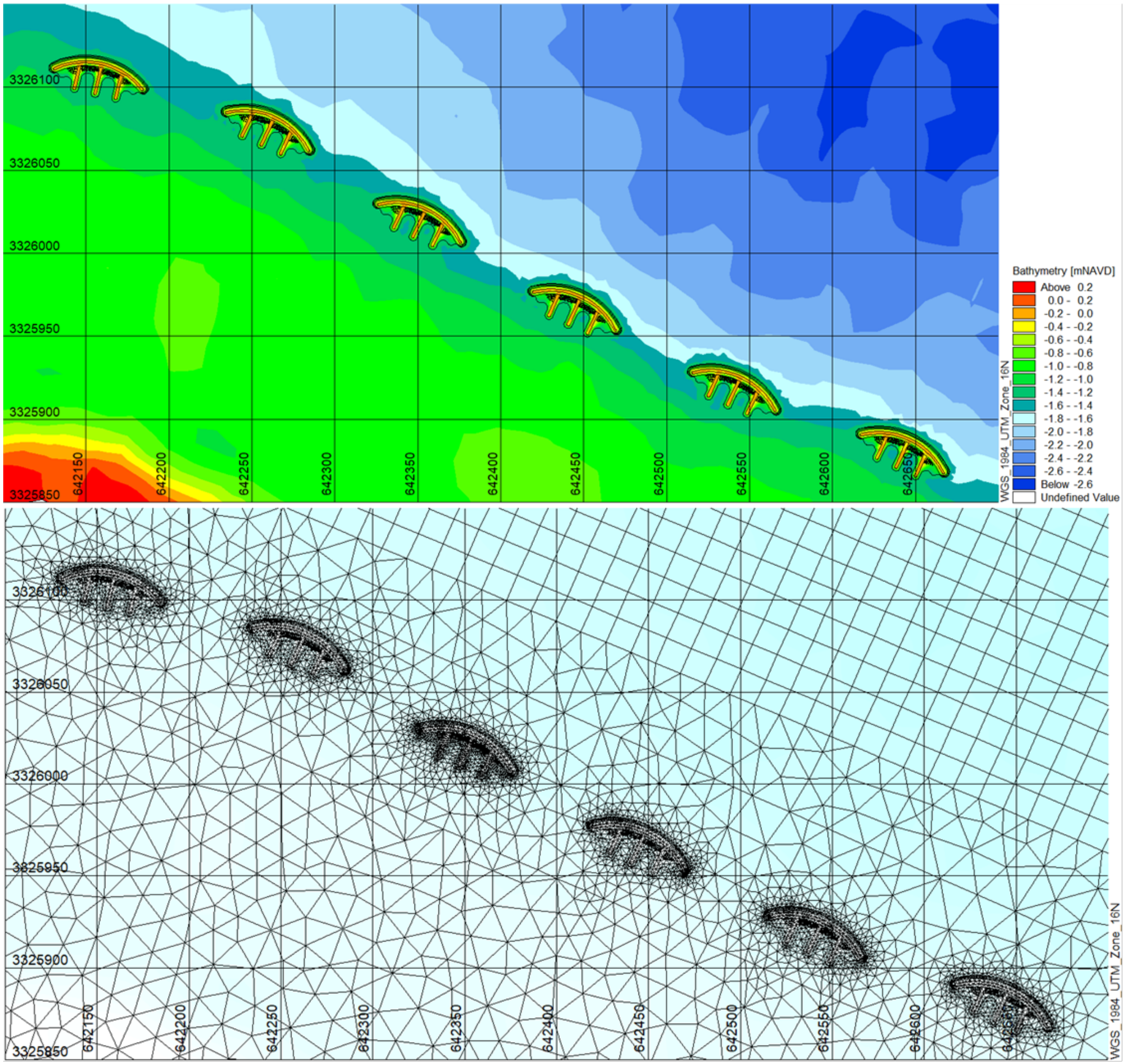


Notes:

Upper: Mesh bathymetry

Lower: Mesh resolution

Figure 6-2. Mesh Bathymetry and Resolution in the Oyster Reef Breakwater Site's Project Vicinity

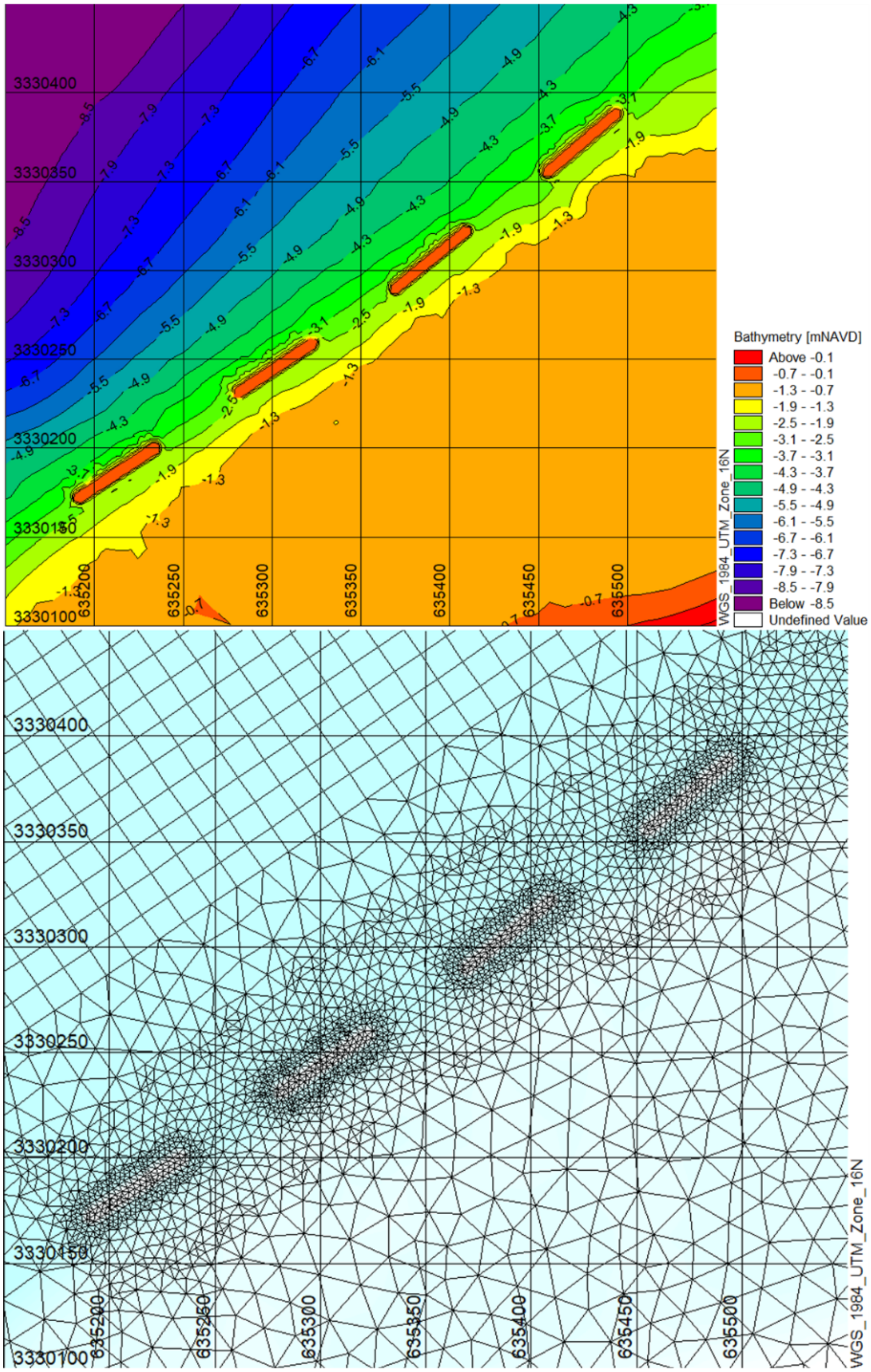


Notes:

Upper: Mesh bathymetry

Lower: Mesh resolution

Figure 6-3. Mesh Bathymetry and Resolution in the Living Shoreline Site's Project Vicinity



Notes:

Upper: Mesh bathymetry

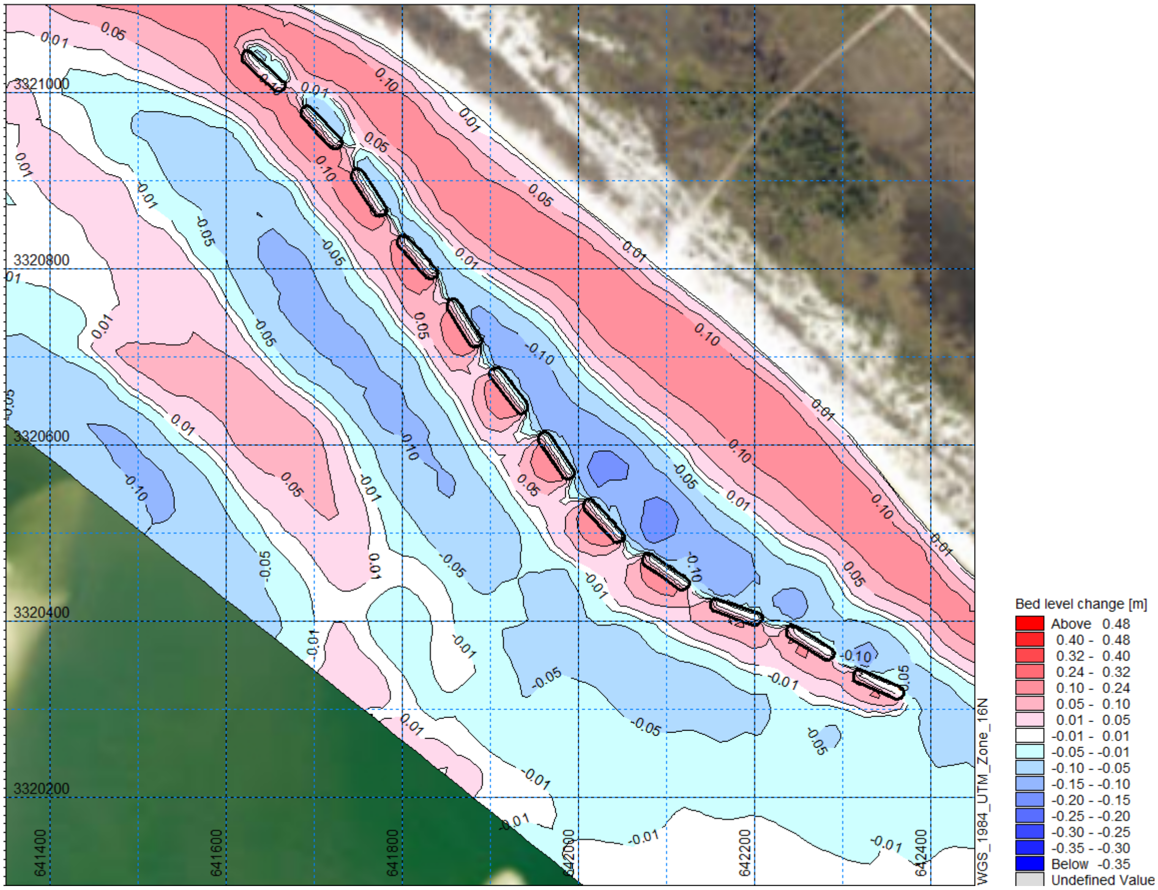
Lower: Mesh resolution

To account for the nonerodable surface represented by the submerged structures, a threshold sediment layer thickness was specified over the nonerodable surfaces. This option is useful when simulating sand transport in areas with nonerodable surfaces. If the local layer thickness is less than the defined threshold thickness, the total transport rate is reduced according to a parabolic formulation, resulting in minimal sediment transport. Herein, the threshold layer thickness was specified as 0.006 meter.

The calibrated model parameter (that is, the maximum bed level change rate per day) was specified as 0.0005 meter based on the comparison of annual sedimentation rates, as discussed in Section 3.

The resulting spatial distribution of annual sedimentation rates is shown on Figures 6-4 through 6-6 for all three sites.

Figure 6-4. Modeled Distribution of Annual Sedimentation Rate for the Submerged Shoreline Stabilization Site (Preferred Layout)

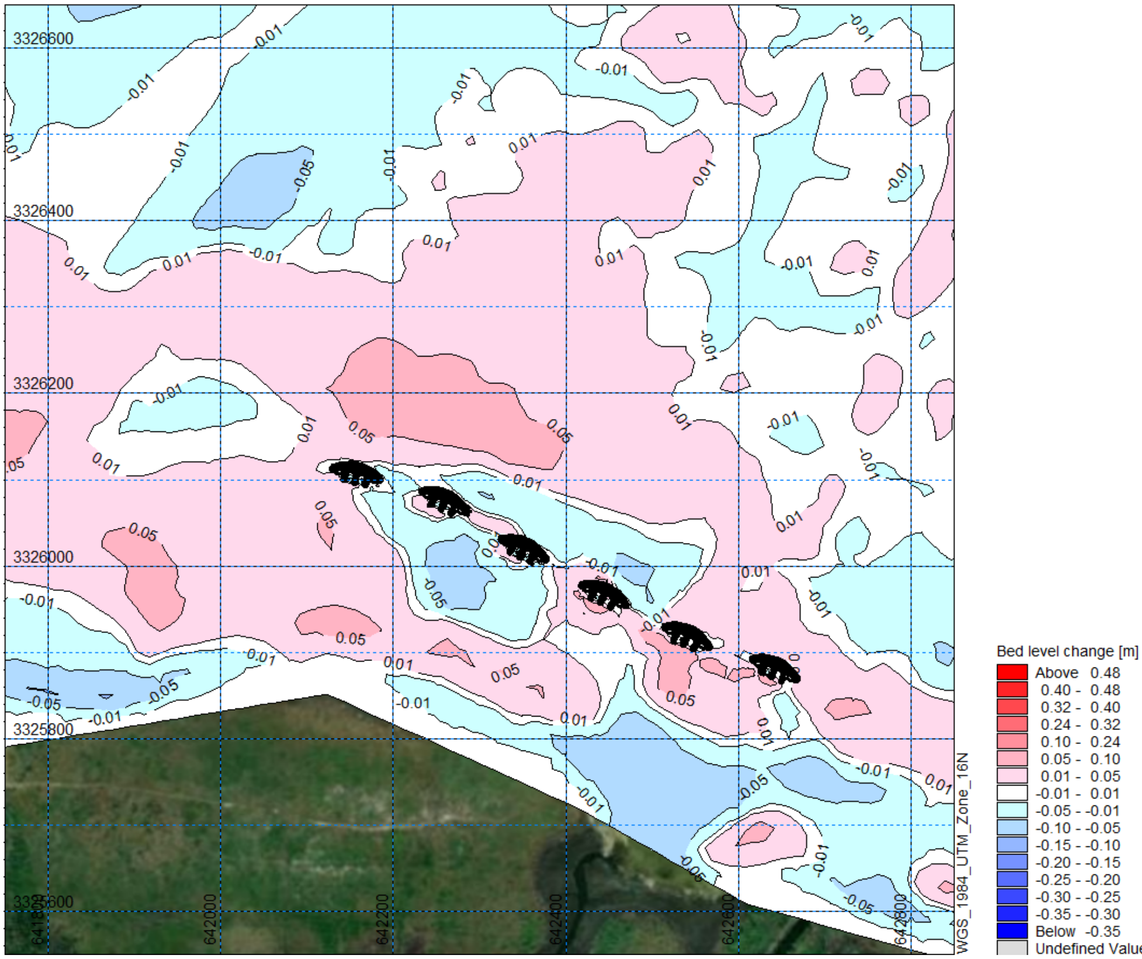


Notes:

Red color denotes sedimentation; blue denotes erosion.

The thick black lines denote the preferred layout.

Figure 6-5. Modeled Distribution of Annual Sedimentation Rate for the Oyster Reef Breakwater Site (Preferred Layout)

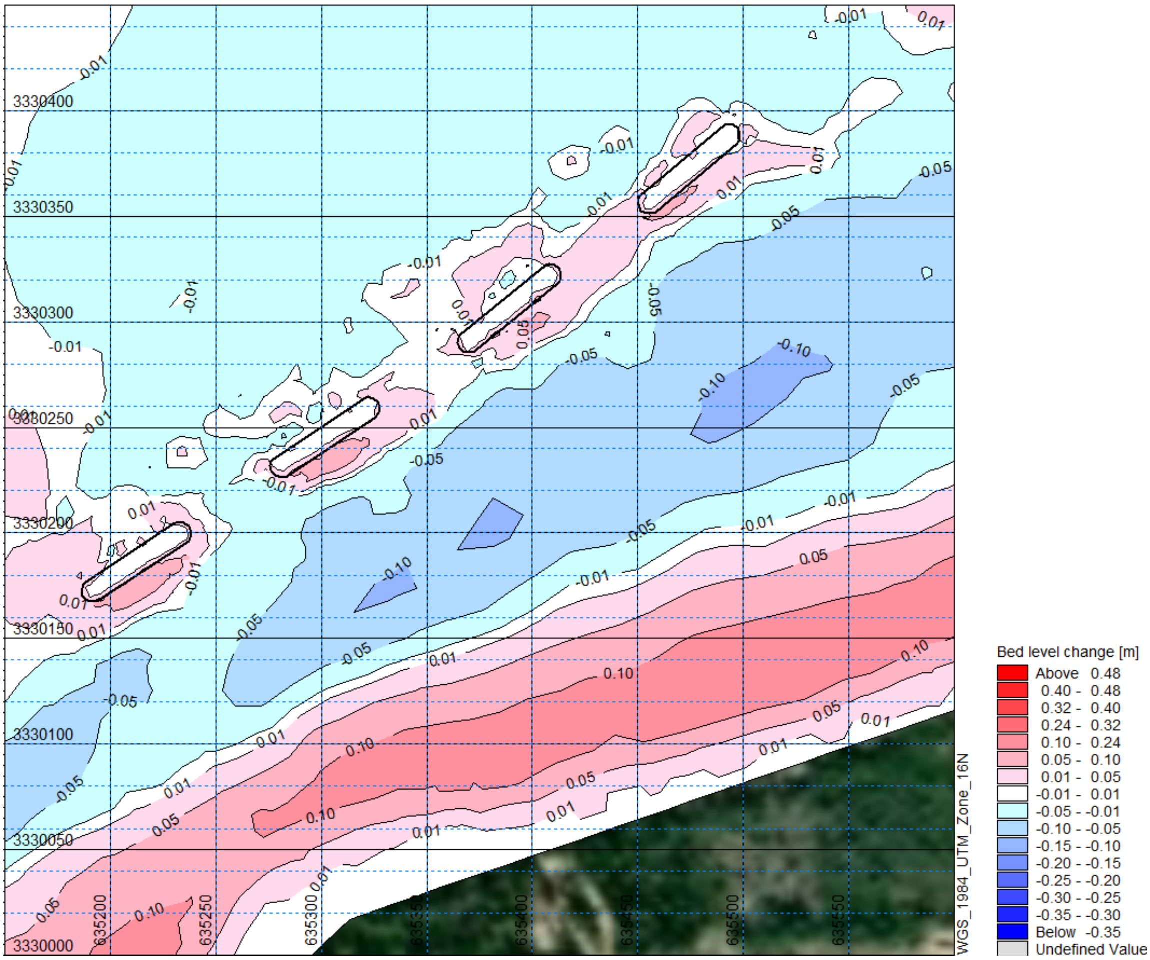


Notes:

Red color denotes sedimentation; blue denotes erosion.

The full black lines denote the preferred layout.

Figure 6-6. Modeled Distribution of Annual Sedimentation Rate for the Living Shoreline Site (Preferred Layout)



Notes:

Red color denotes sedimentation; blue denotes erosion.

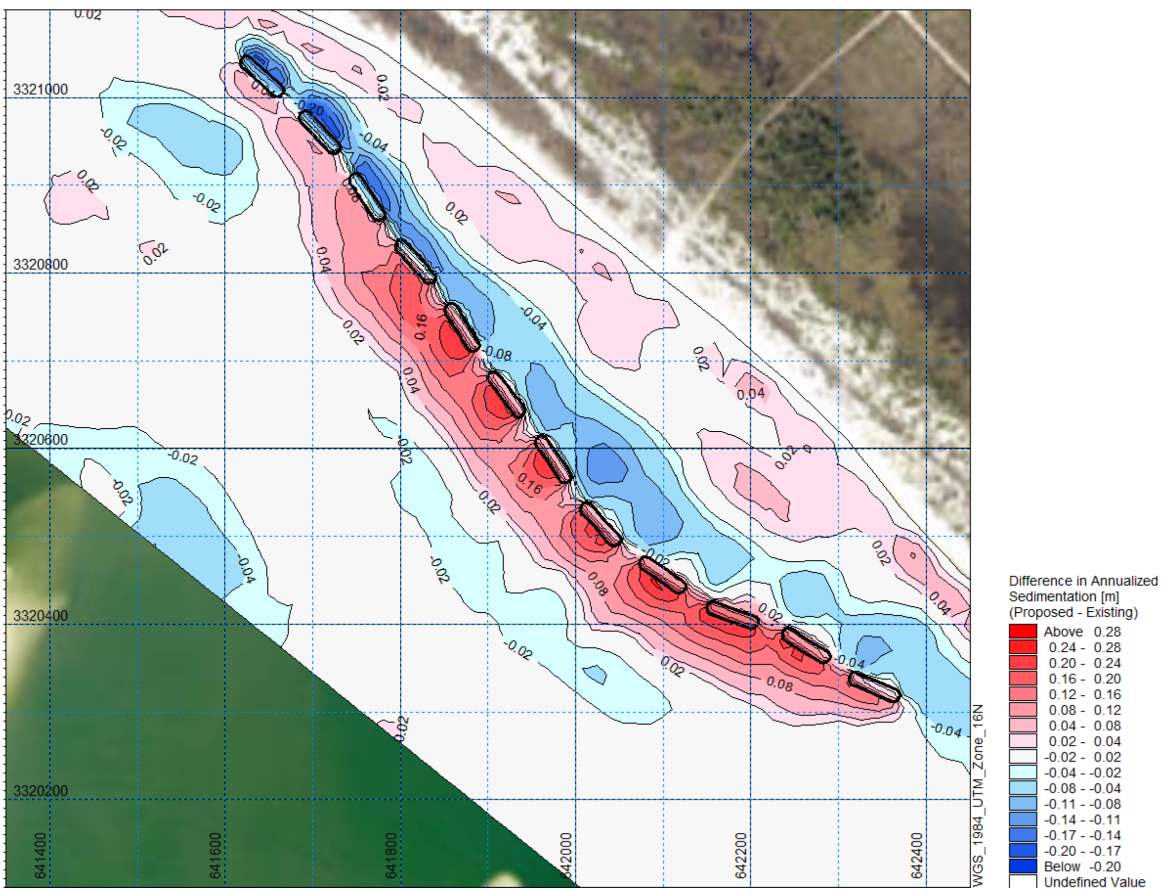
The thick black lines denote the preferred layout.

A plot showing the difference of modeled distribution of the annual sedimentation rate between preferred layout (Figure 6-4) and existing conditions (Figure 4-1) for the Submerged Shoreline Stabilization site is shown on Figure 6-7.

Relative to the sedimentation pattern for the existing condition, the following impacts in the presence of the structures are observed:

- The nearshore sedimentation rate is enhanced to the tune of 0.1 meter on average, which is likely due to wave sheltering.
- The belt of erosion abutting the landward edge of the structure results in an enhanced erosion rate up to as much as 0.1 meter near the center of the structure line.
- There is now a sedimentation strip immediately seaward of the structure line of up to 0.05 meter.

Figure 6-7. Difference Plot of the Modeled Distribution of Annual Sedimentation Rate between Preferred Layout and Existing Conditions for the Submerged Shoreline Stabilization Site



Notes:

Red color denotes increased sedimentation; blue denotes increased erosion relative to the existing conditions.

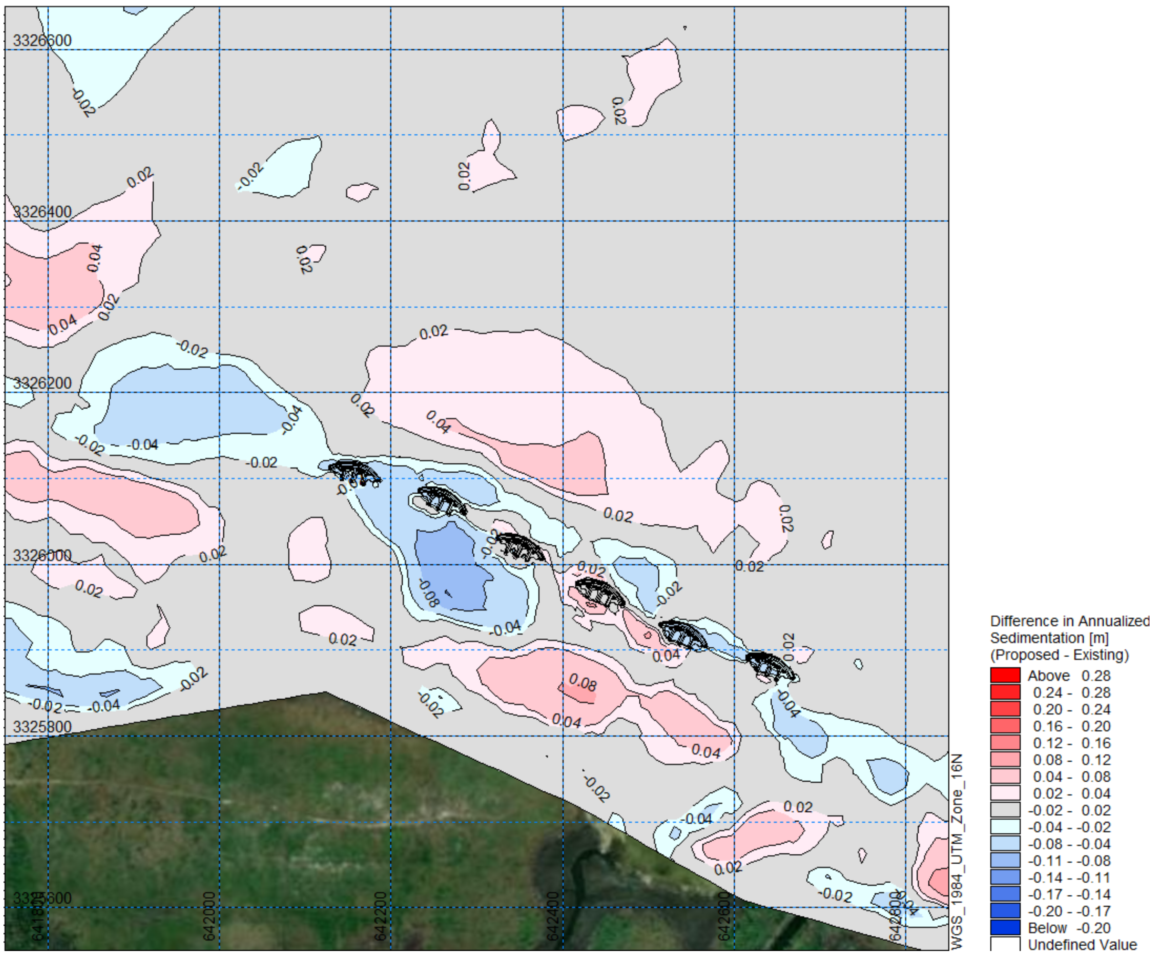
The thick black lines denote the preferred layout.

A plot showing the difference of modeled distribution of the annual sedimentation rate between preferred layout (Figure 6-5) and existing conditions (Figure 4-2) for the Oyster Reef Breakwater site is shown on Figure 6-8.

It is observed that relative to the sedimentation pattern for the existing condition shown, the following impacts in the presence of the structures are observed:

- The overall changes are minimal except for some shifting discrete zones around the structure line of sedimentation and erosion but basically maintaining the same annual rates of +/-0.05 meter.

Figure 6-8. Difference Plot of the Modeled Distribution of Annual Sedimentation Rate between Preferred Layout and Existing Conditions for the Oyster Reef Breakwater Site



Notes:

Red color denotes increased sedimentation; blue denotes increased erosion relative to the existing conditions.

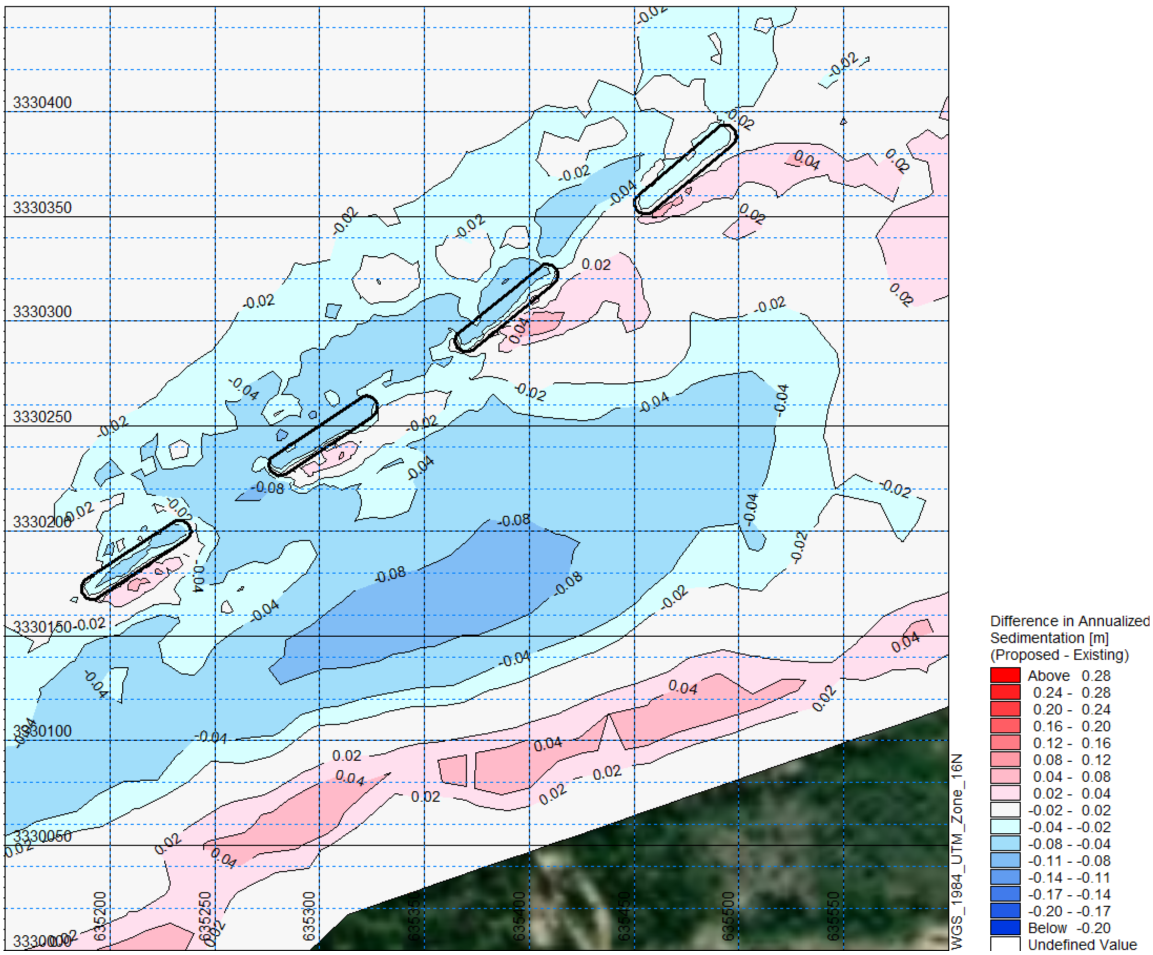
The full black lines denote the preferred layout.

A plot showing the difference of modeled distribution of the annual sedimentation rate between preferred layout (Figure 6-6) and existing conditions (Figure 4-3) for the Living Shoreline site is shown on Figure 6-9.

It is observed that relative to the sedimentation pattern for the existing condition, the following impacts in the presence of the structures are observed:

- The overall changes are minimal except for a slight enhanced sedimentation and erosion rates of up to +/-0.1 meter.

Figure 6-9. Difference Plot of the Modeled Distribution of Annual Sedimentation Rate between Preferred Layout and Existing Conditions for the Living Shoreline Site



Notes:

Red color denotes increased sedimentation; blue denotes increased erosion relative to the existing conditions.

The thick black lines denote the preferred layout.

7. Extreme HD and Wave Modeling – Preferred Layout

Extreme HD and wave modeling was conducted to determine the design flow and wave conditions required for the detailed design of the proposed structures. The modeling was conducted using the calibrated models where the boundary conditions and wind forcing remained unchanged as those used in the extreme modeling for the existing conditions, as previously discussed in the 60% Design Reports (Jacobs 2024a, 2024b, 2024c). The simulations were conducted for the adopted design storm events (that is, 50 years for the Submerged Shoreline Stabilization site and 25 years for the Oyster Reef Breakwater and Living Shoreline sites).

The following simulations were conducted:

- 25-year event for the Oyster Reef Breakwater and Living Shoreline sites
- 25-year event +1.96 feet of sea level rise (SLR) for the Oyster Reef Breakwater and Living Shoreline sites
- 50-year event for the Submerged Shoreline Stabilization site
- 50-year event +3.67 feet of SLR for the Submerged Shoreline Stabilization site

The results are presented as spatial distributions of maximum current speeds and wave heights, as illustrated on Figure 7-1 and Figure 7-2 for the Submerged Shoreline site. All the resulting plots are contained in Appendix A (maximum current speeds) and Appendix B (maximum wave heights).

Refined plots zoomed in on the vicinity of the structures upon the request of the design team and are illustrated on Figure 7-3 and Figure 7-4 for the Oyster Reef Breakwater and Figure 7-5 and Figure 7-6 for the Living Shoreline site to determine the largest current speed for design.

Based on Figure 7-3, the present condition (that is, without the SLR) for the Oyster Reef Breakwater site had the following results:

- Maximum everywhere: over the reef crest at the white square = 1.17 meters per second
- Maximum seaward at the east end = 0.68 meter per second
- Maximum seaward at the west end = 0.60 meter per second
- The maximum in the gaps and landward of the reefs is 0.40 meter per second.

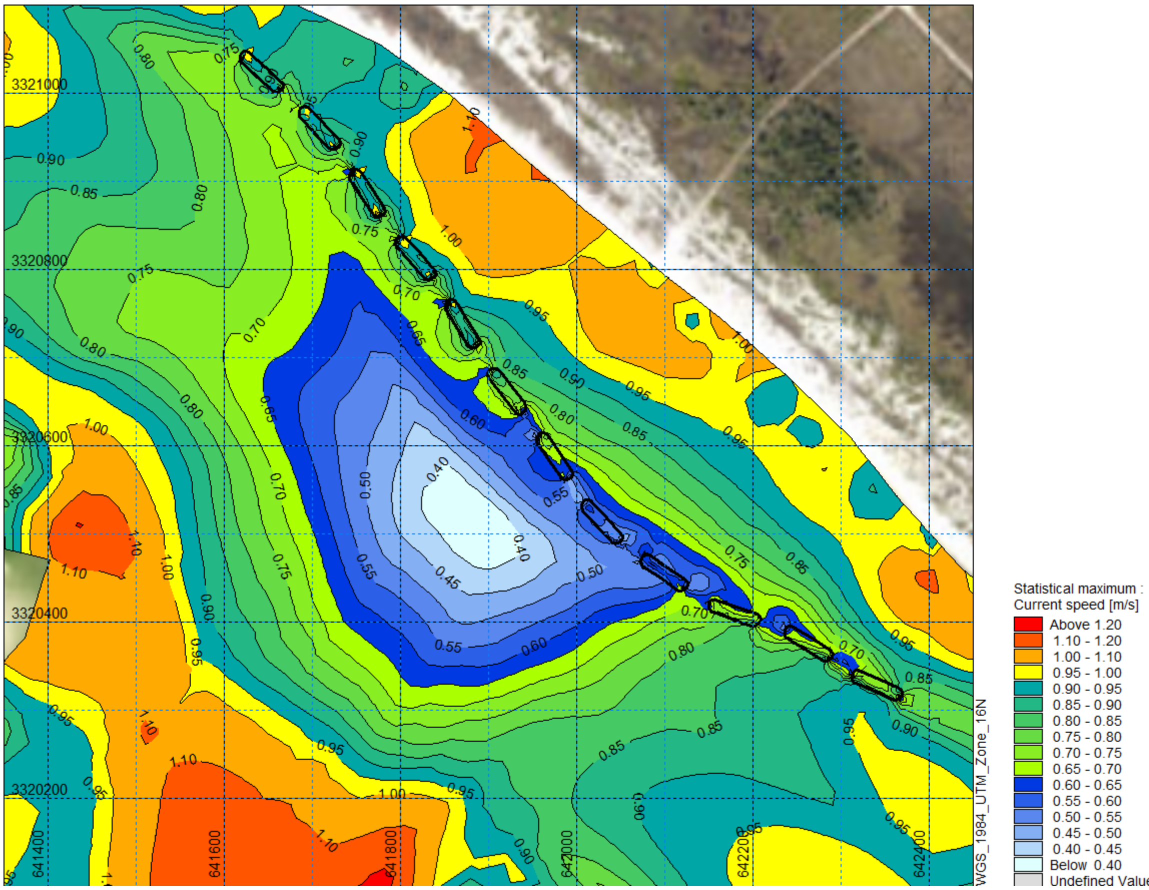
Based on Figure 7-4, the future condition (that is, with SLR) showed the maximum current speed on the landward side (0.57 meter per second) and in the gaps (0.52 meter per second). These are both higher than those without the SLR case (Figure 7-3). At the same time, the maximum current speed over the crest is also much lower now because of the increased water level over it.

Based on Figure 7-5, the present condition (that is, without the SLR) for the Living Shoreline site had the following results:

- Maximum everywhere: over the reef crest (at the east end) = 0.76 meter per second
- Maximum seaward (at the east end) = 0.82 meter per second
- Maximum landward (at the east end) = 0.83 meter per second
- The maximum in the gaps (at the east end) is 0.71 meter per second.

Based on Figure 7-6, the future condition (that is, with SLR) showed maximum current speeds on the seaward side (0.79 meter per second) and landward side (0.78 meter per second), as well as in the gaps (0.64 meter per second). There are all lower than those without the SLR case (Figure 7-5). On the other hand, the maximum current speed over the crest is now higher at 0.87 meter per second.

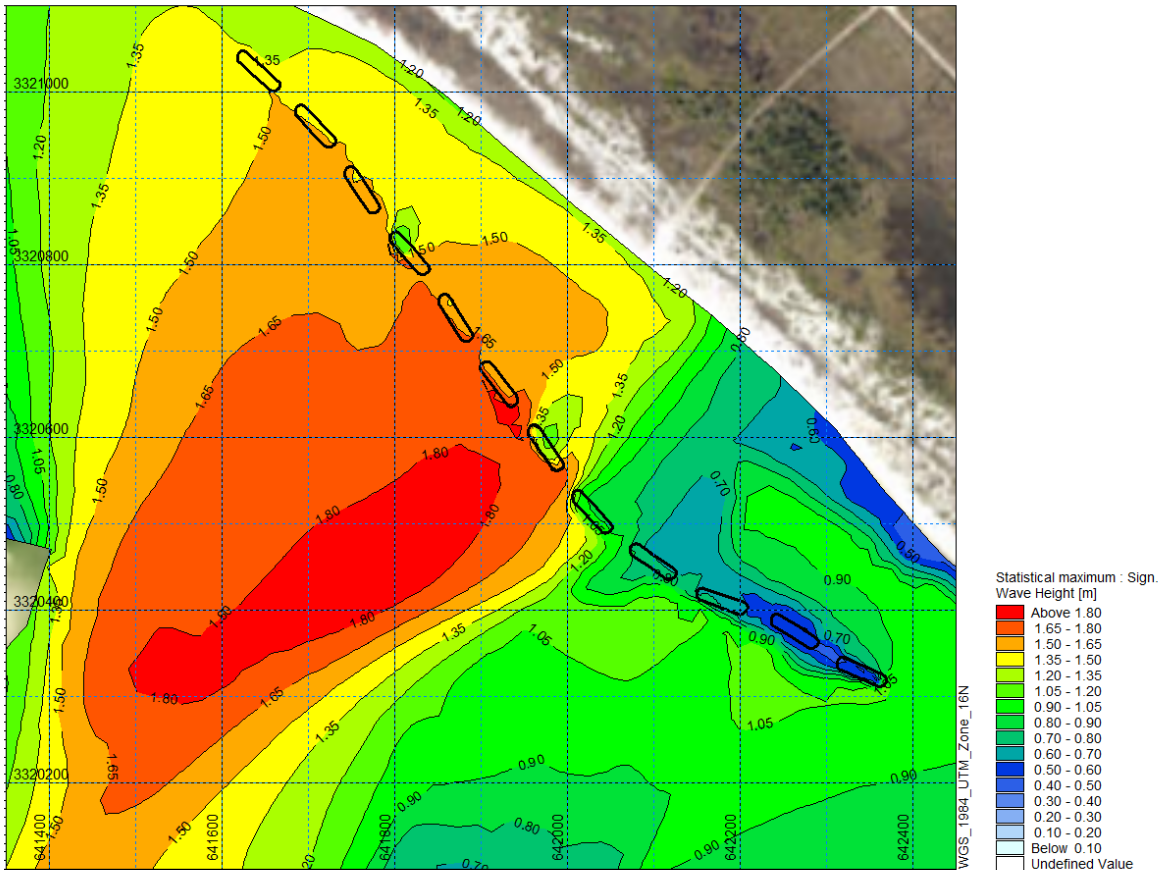
Figure 7-1. Spatial Distribution of Maximum Current Speeds at the Submerged Shoreline Stabilization Site (50-year Event, Proposed Condition)



Note:

The thick black lines denote the footprint of the preferred layout.

Figure 7-2. Spatial Distribution of Maximum Wave Heights at the Submerged Shoreline Stabilization Site (50-year Event; Proposed Condition)



Note:

The thick black lines denote the footprint of the preferred layout.

Figure 7-3. Zoomed Coverage of the Spatial Distribution of Maximum Current Speeds at the Oyster Reef Breakwater Site (25-year Event)

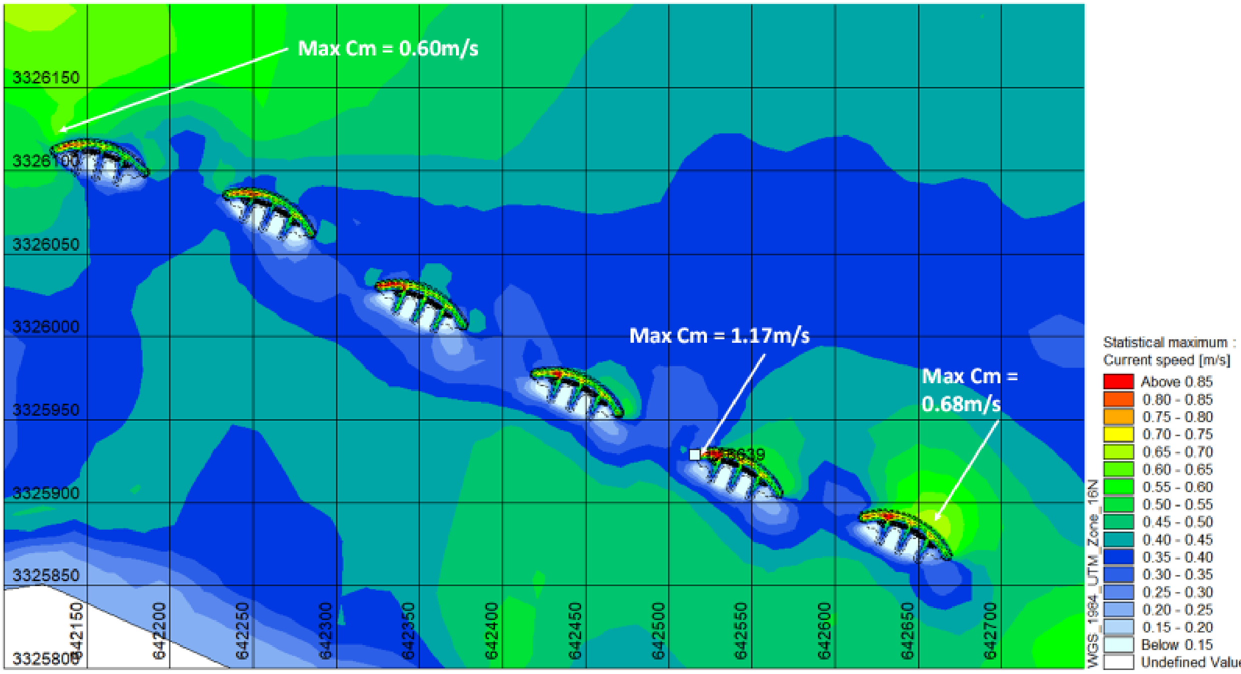


Figure 7-4. Zoomed Coverage of the Spatial Distribution of Maximum Current Speeds at the Oyster Reef Breakwater Site (25-year Event,1.96-foot SLR Event)

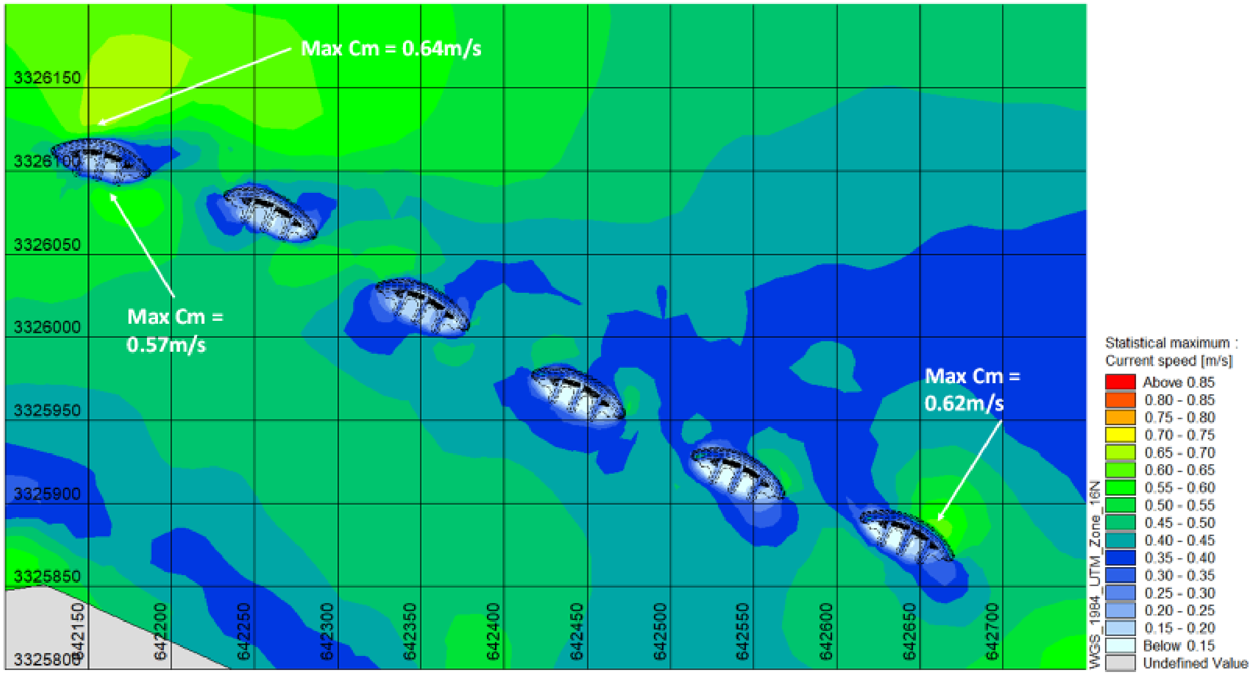


Figure 7-5. Zoomed Coverage of the Spatial Distribution of Maximum Current Speeds at the Living Shoreline Site (25-year Event)

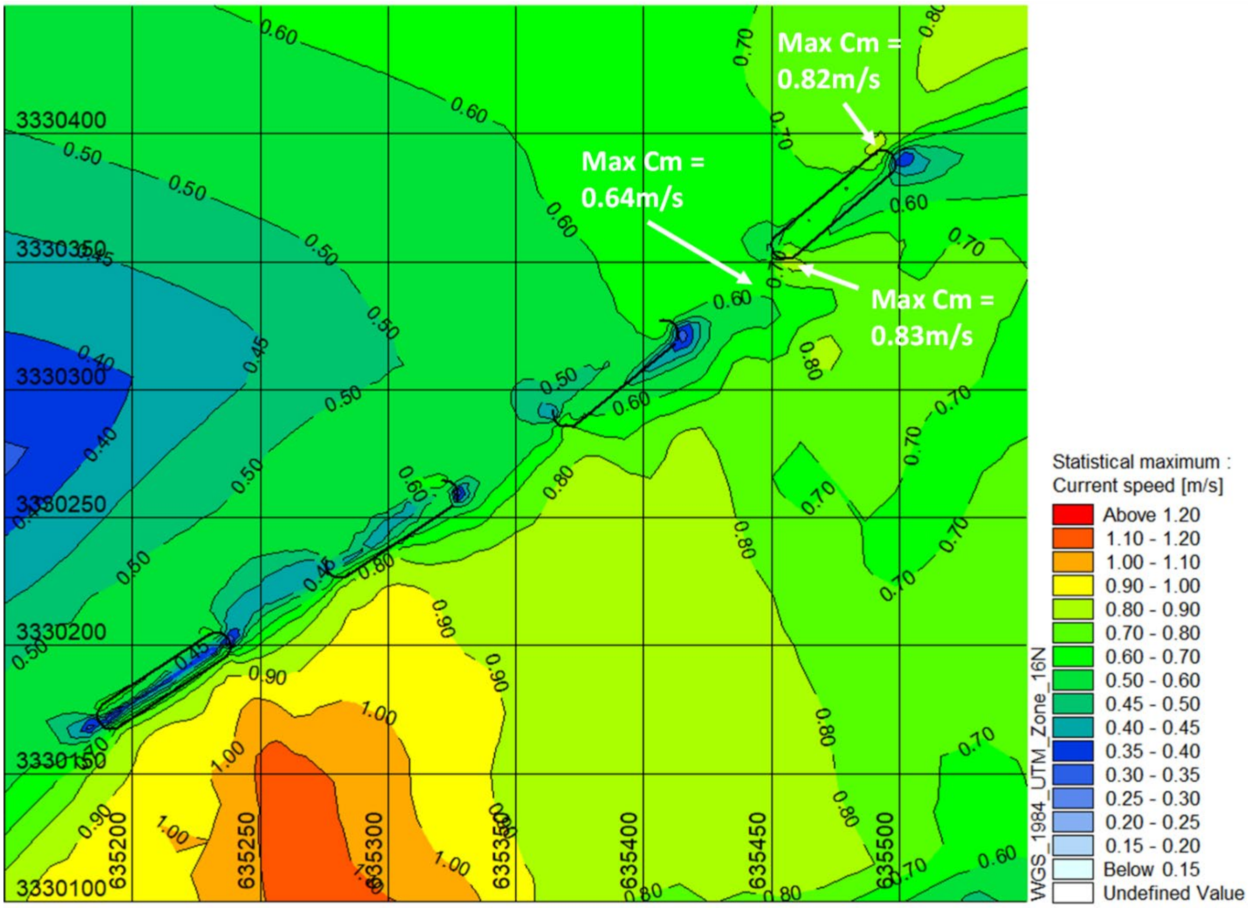
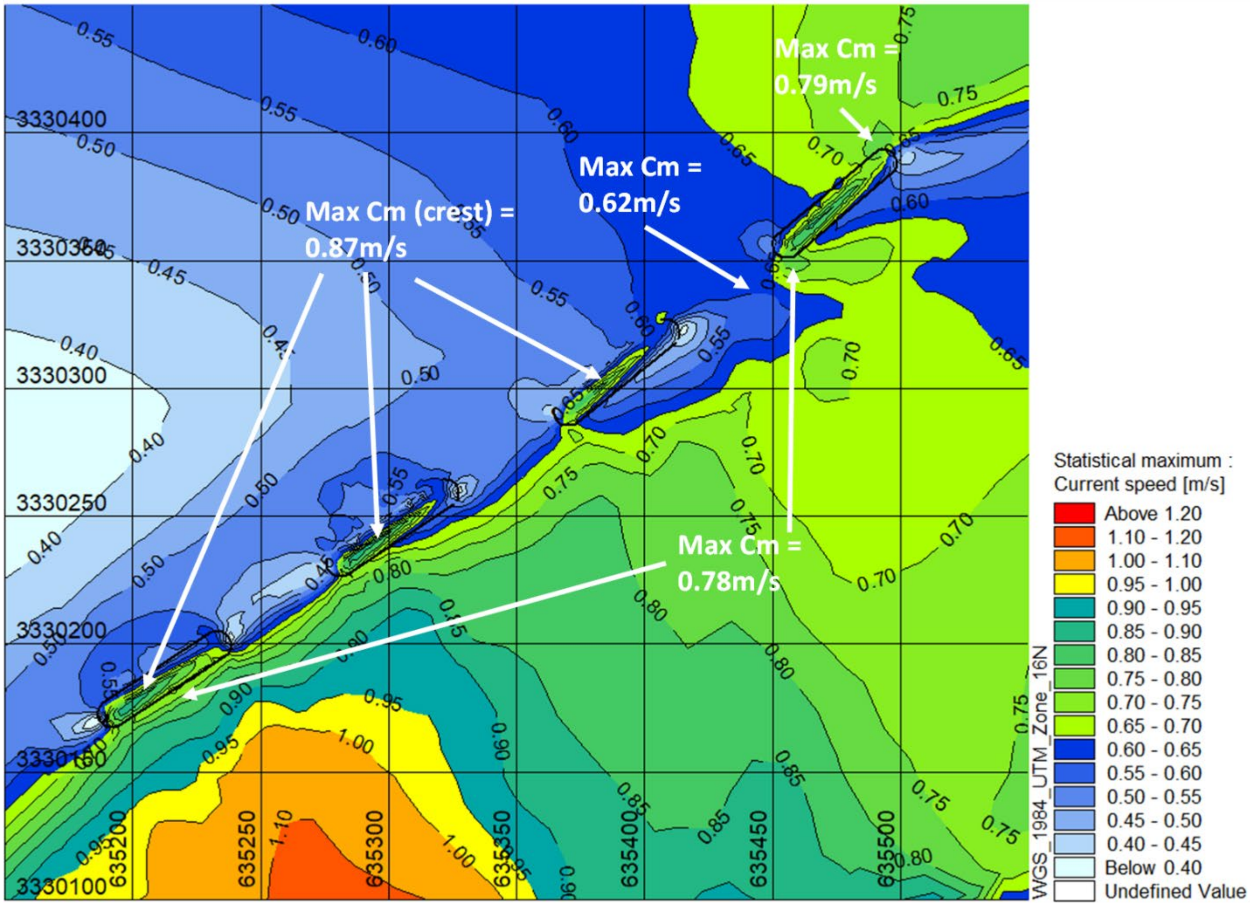


Figure 7-6. Zoomed Coverage of the Spatial Distribution of Maximum Current Speeds at the Living Shoreline Site (25-year, +1.9-foot SLR Event)



8. Conclusions and Recommendations

The present study is a follow-up to the previously completed 60% design stage for calibrated models (Jacobs 2023) and builds on the previous study by focusing on the following primary tasks:

- Using annual sediment transport modeling of the existing conditions (baseline) at the three project sites to determine annual sedimentation rates. The three sites are the Submerged Shoreline Stabilization site, located in the coastal area but protected by a barrier island broken by an entrance channel, and the Oyster Reef Breakwater and Living Shoreline sites, both of which are located within the East Bay.
- Applying the calibrated models in wave attenuation analysis to assist in layout optioneering and to arrive at the preferred layouts.
- Using annual sediment transport modeling of the preferred layouts at the three sites to determine sedimentation impacts induced by the preferred layouts.
- Applying the calibrated models to determine extreme flows and waves associated with the preferred layouts for design optimization.

The historical sedimentation rates were derived from annualizing the difference between two time-separated bathymetries. The modeled sedimentation rates in the project area for the existing conditions were estimated to be slightly depositional at an average rate of 0.05 meter per year for the abutting nearshore belt. Further seaward, the area trends toward being slightly erosional at an average rate of up to –0.1 meter per year, except at the Submerged Shoreline Stabilization site, where, because the coastal site is exposed to larger waves due to the presence of the entrance bar, the erosional rate can reach up to –0.15 meter per second.

The accuracy of the modeled results could be potentially affected by the following three sources of uncertainty:

- Accuracy of the annual historical sedimentation rates
- Dynamic nature of the entrance bar to the Submerged Shoreline Stabilization site
- Interannual variation in the ambient wind climate, which is a significant driver for flows and waves that, in turn, drive the movement of sediments

Wave attenuation of different layout schemes was investigated via quasi-stationary wave modeling where the crest elevation of the detached breakwaters is set at MLLW, which implies that the breakwater will be submerged below the water surface to varying degrees most of the time. Such a design leads to less design wave load and the use of less construction material, both of which contribute to cost savings. At the same time, higher waves will also be experienced in the lee, and the impact of these potentially higher waves was investigated herein.

Generally, increased water levels (that is, increased wave heights over the structure crest due to greater water depth) decreased wave attenuation across all transects (that is, larger waves at the landward side of the structures). Moreover, the combined action of the multiple gaps leads to varying low wave attenuation zones in the lee areas of the breakwater structures depending on the number of detached breakwaters and gap width. This potentially impacts the sustainability of the SAV area.

The wave attention analysis is a function of different layouts and water level variations. These were fed to the design team as inputs during design optimization. The preferred layouts for each site were applied in the subsequent sediment transport modeling and extreme flow and wave modeling for the preferred layouts.

These preferred layouts are as follows:

- Submerged Shoreline Stabilization: 12 segments of 200-foot-long straight submerged breakwaters spaced uniformly 100 feet apart along a curvilinear alignment.
- Oyster Reef Breakwater: Six segments of 200-foot-long curvilinear submerged breakwaters spaced uniformly 150 feet apart along a nearly straight alignment where the leeward side consists of a series of finger spurs flanked by precast DARPA units.
- Living Shoreline: Four segments of 200-foot-long straight submerged breakwaters spaced uniformly 150 feet apart along a shore parallel straight alignment.

The impacts of the proposed structures were evaluated via sediment transport modeling and were related to those for the existing condition, as described in the following subsections.

8.1 Submerged Shoreline Stabilization

The nearshore sedimentation rate is enhanced to the tune of 0.1 meter on average, which is likely due to wave sheltering.

The belt of erosion abutting the landward edge of the structure causes an enhanced erosion rate up to as much as -0.1 meter near the center of the structure line.

There is now a sedimentation strip immediately seaward of the structure line of up to 0.05 meter.

8.2 Oyster Reef Breakwater

The overall changes are minimal except for some shifting discrete zones around the sedimentation and erosion structure line, but they maintain the same annual rates of +/-0.05 meter.

8.3 Living Shoreline

The overall changes are minimal except for slightly enhanced sedimentation and erosion rates of up to +/- 0.1 meter.

Extreme HD and wave modeling were conducted to determine the design flow and wave conditions required for the detailed design of the proposed structures. The simulations were performed for the adopted design storm events (that is, 50 years for the Submerged Shoreline Stabilization site and 25 years for the Oyster Reef Breakwater and Living Shoreline sites).

9. References

Danish Hydraulic Institute (DHI). 2024a. *MIKE 21 Spectral Wave Flexible Mesh (FM) Module: User Guide.*

Danish Hydraulic Institute (DHI). 2024b. *MIKE 21 Flow Module Flexible Mesh (FM): User Guide.*

Danish Hydraulic Institute (DHI). 2024c. *MIKE 21 Sand Transport Module: User Guide.*

Danish Hydraulic Institute (DHI). 2024d. *MIKE 21 Toolbox: User Guide.*

Doering, J.C. and A.J. Bowen. 1995. "Parameterization of orbital velocity asymmetries of shoaling and breaking waves using bispectral analysis." *Coastal Engineering*. Vol. 16, Issues 1-2. September. p. 15-23.

Jacobs. 2023. *Tyndall Air Force Base – Regional Hydrodynamic and Wave Transformation Modeling – 60 Percent Design – Calibrated Model.* Draft Technical Memorandum. Submitted to The Nature Conservancy TNC), May 2023.

Jacobs. 2024a. *Tyndall Pilot Project, Submerged Shoreline Stabilization: 60% Basis of Design Report.* May 2024.

Jacobs. 2024b. *Tyndall Pilot Project, Oyster Reef Breakwater: 60% Basis of Design Report.* May 2024.

Jacobs. 2024c. *Tyndall Pilot Project, Living Shoreline: 60% Basis of Design Report.* May 2024.

National Center for Environmental Information (NCEI). 2023. *Continuously Updated Digital Elevation Model (CUDEM) - 1/9 Arc-Second Resolution Bathymetric-Topographic Tiles.* October 19. https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ngdc.mgg.dem:999919.

Ruben Surveying and Mapping. 2023. *Bathymetric, Topographic, and Tidal Water Survey.* February 16. p. 4.

Appendix A
Plots of Spatial Distributions of Maximum Current Speeds

Figure A-1. Spatial Distribution of Maximum Current Speeds at the Submerged Shoreline Stabilization Site, (50-year Event; No Structures in place)

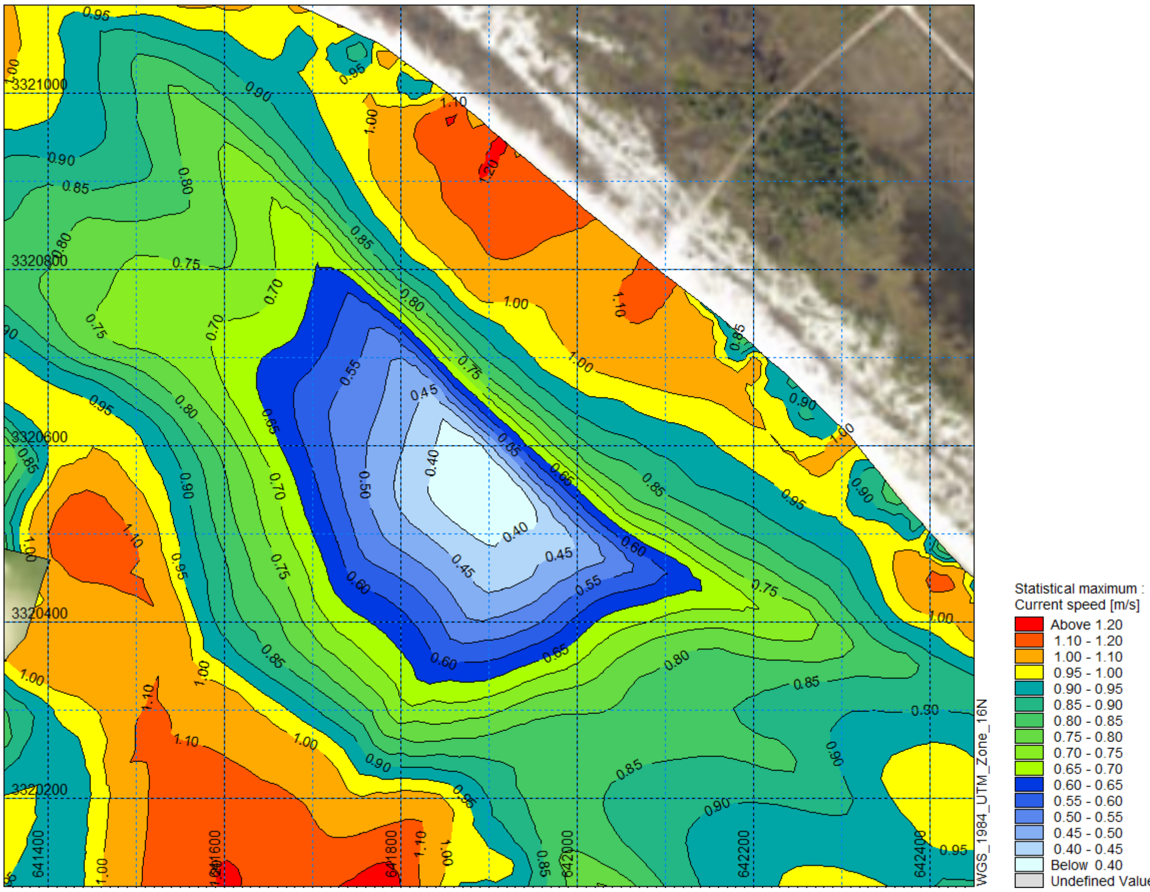


Figure A-2. Spatial Distribution of Maximum Current Speeds at the Submerged Shoreline Stabilization Site, (50-year, +3.67-foot SLR Event; No Structures in place)

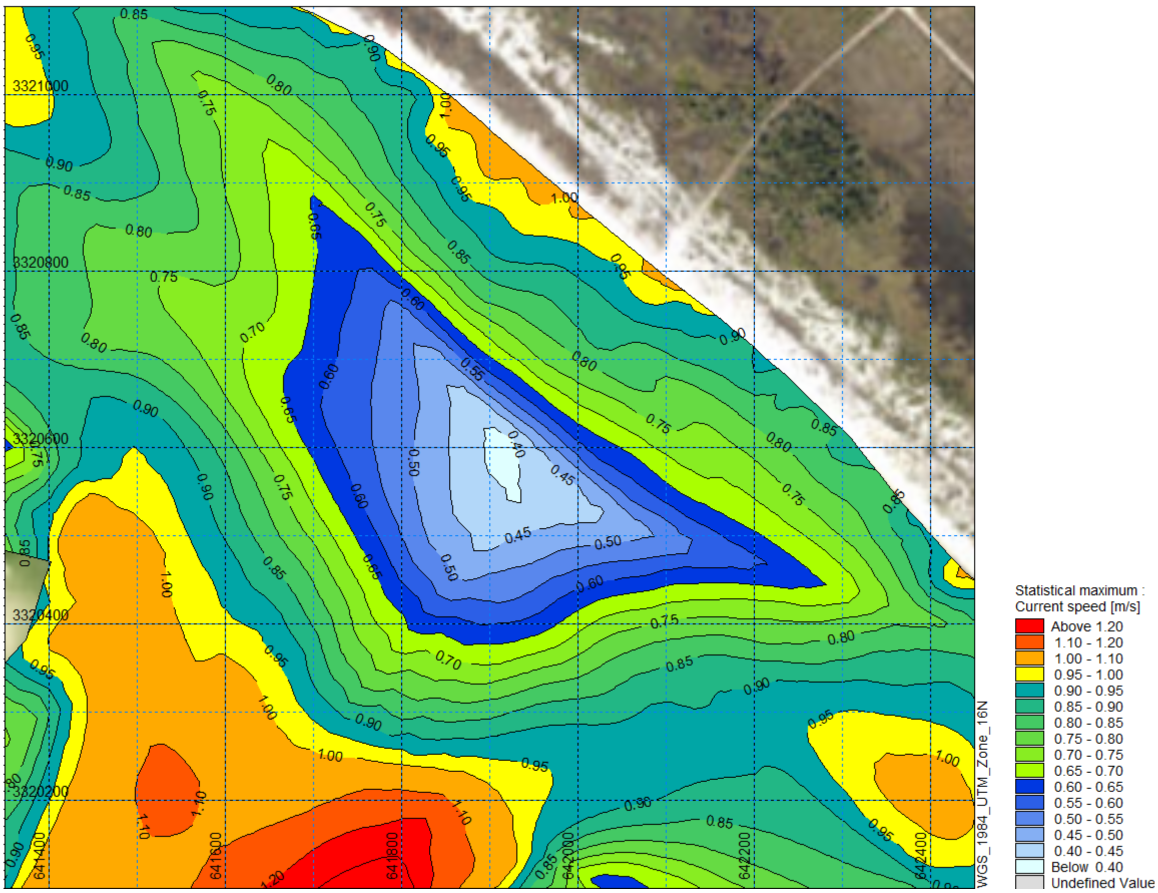


Figure A-3. Spatial Distribution of Maximum Current Speeds at the Submerged Shoreline Stabilization Site, (50-year Event; With Proposed Structures in place)

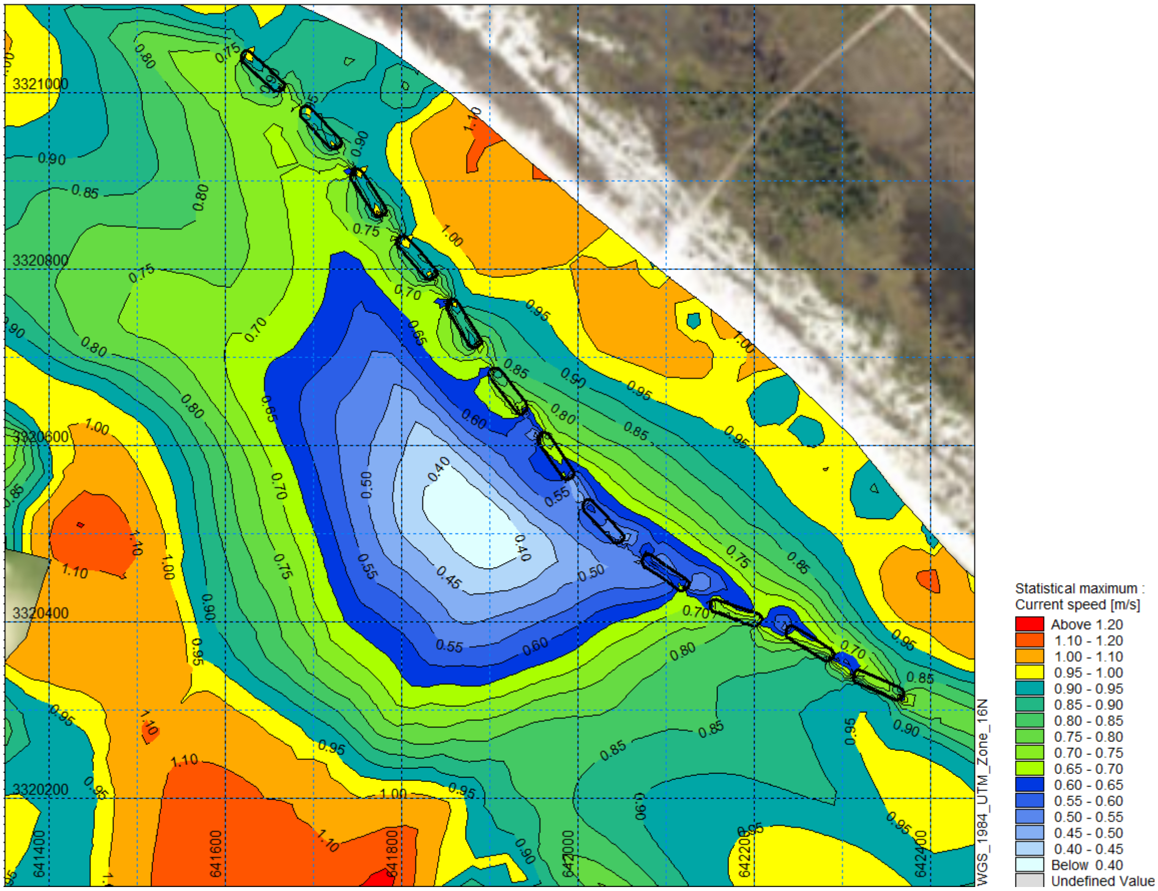


Figure A-4. Spatial Distribution of Maximum Current Speeds at the Submerged Shoreline Stabilization Site, (50-year, +3.67-foot SLR Event; With Proposed Structures in place).

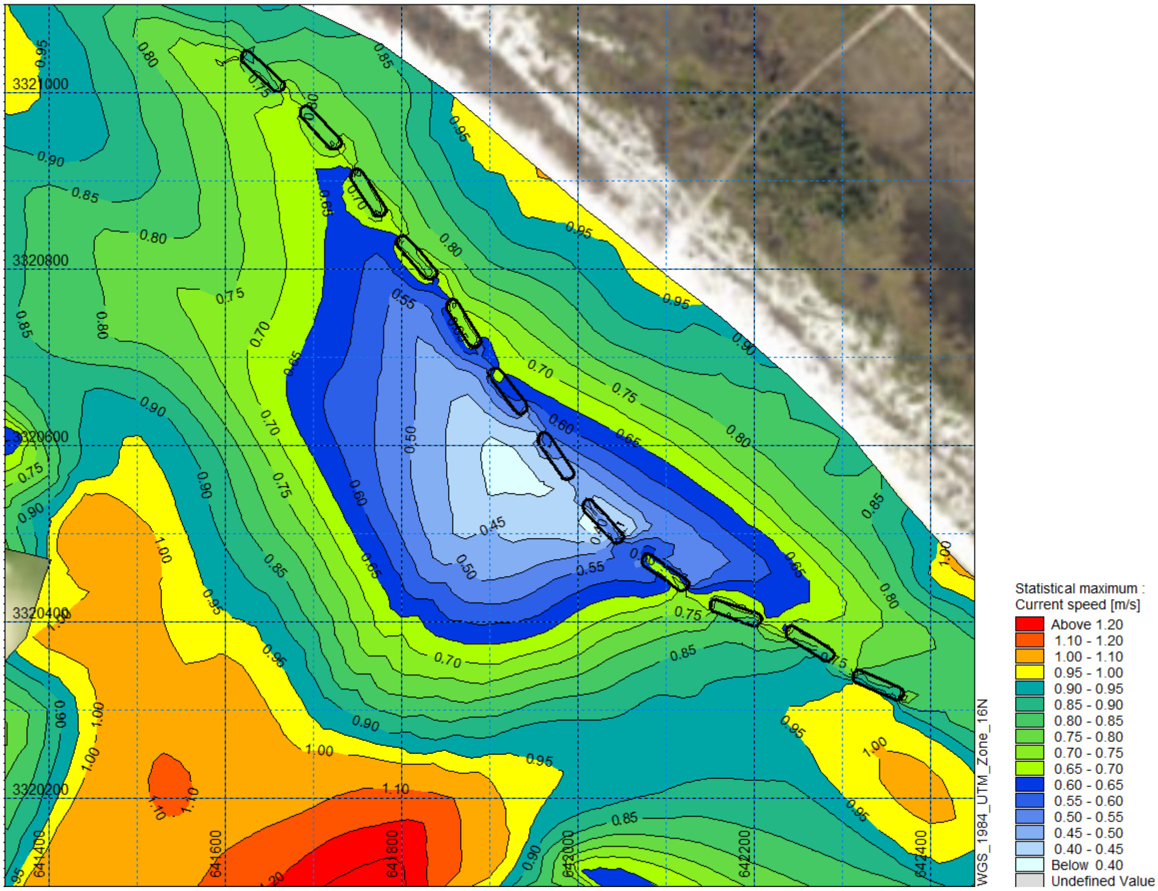


Figure A-5. Spatial Distribution of Maximum Current Speeds at the Oyster Reef Breakwater Site, (25-year Event; No Structures in place)

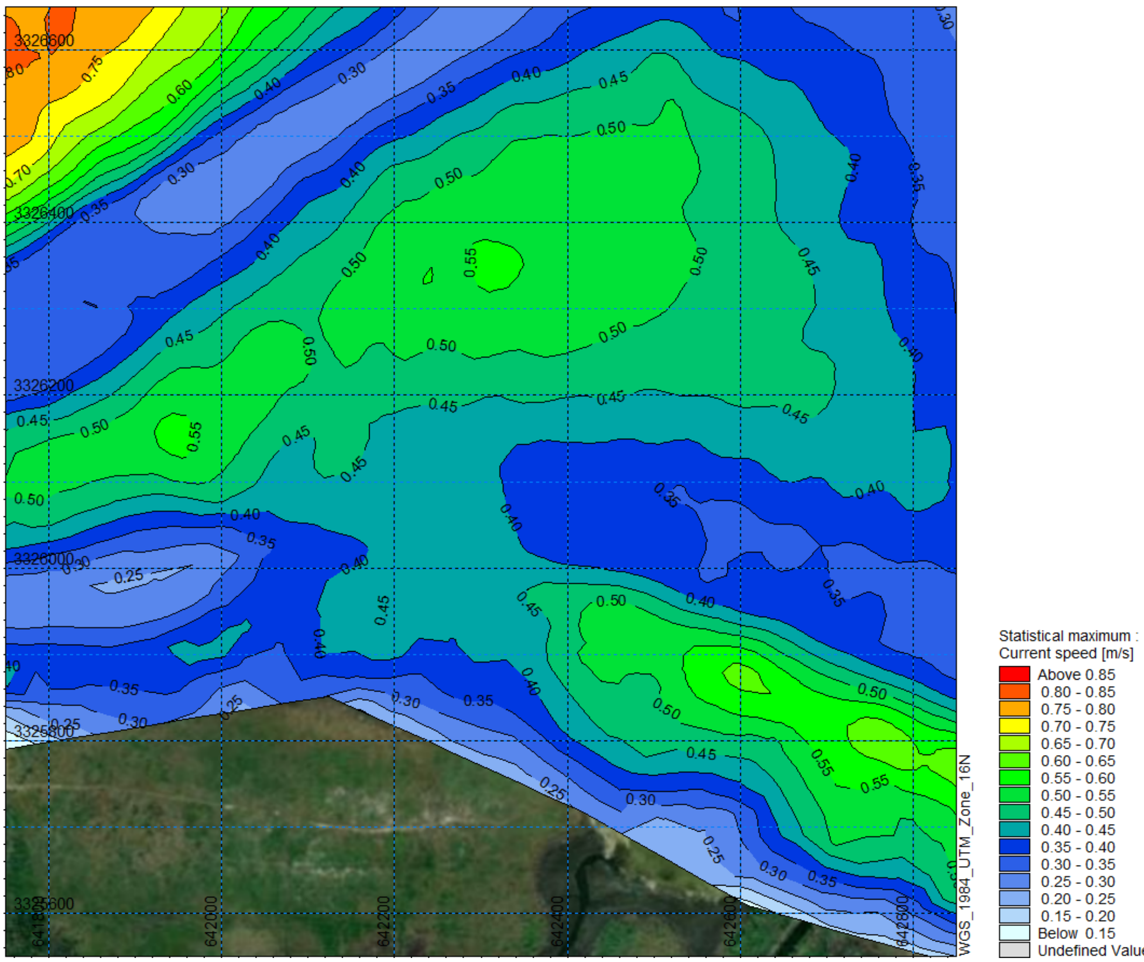


Figure A-6. Spatial Distribution of Maximum Current Speeds at the Oyster Reef Breakwater Site, (25-year, +1.96-foot SLR Event; No Structures in place)

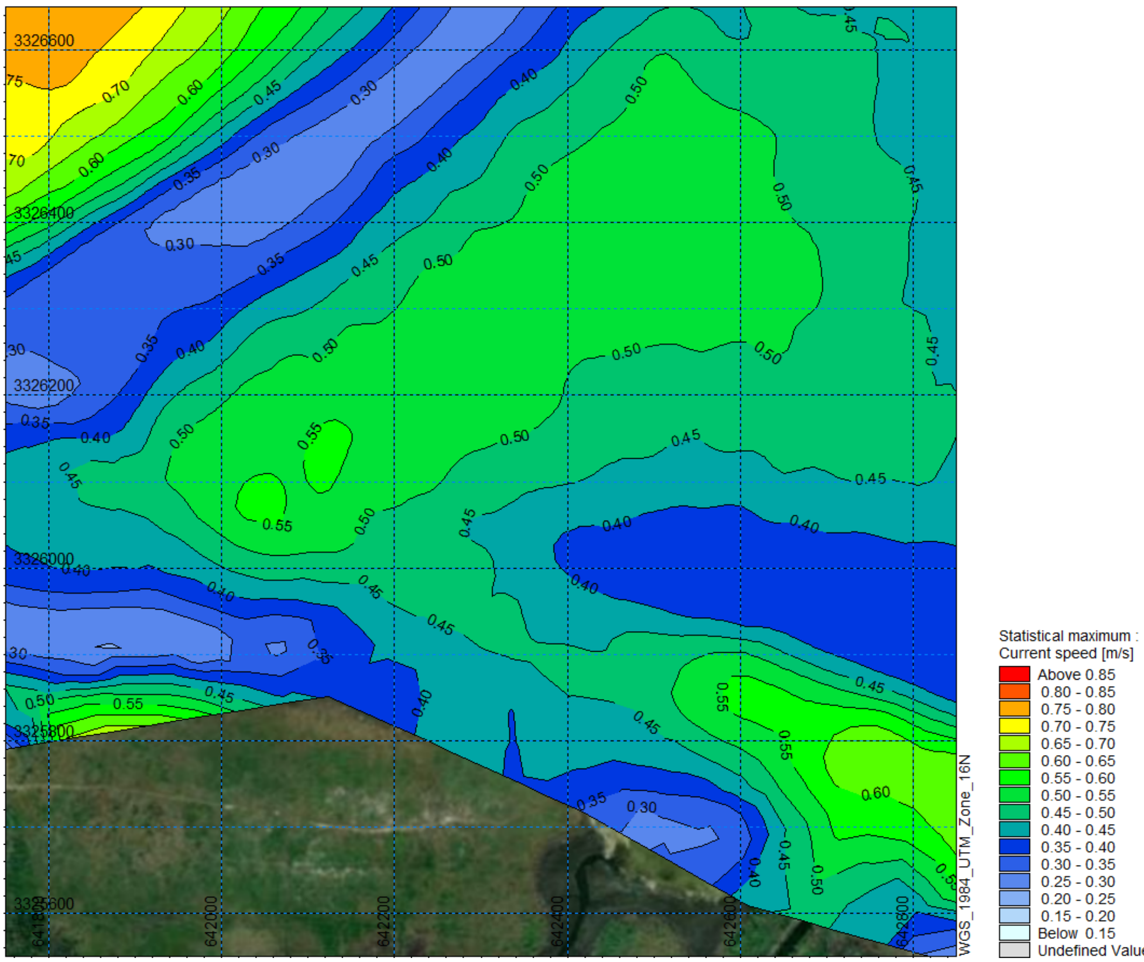


Figure A-7. Spatial Distribution of Maximum Current Speeds at the Oyster Reef Breakwater Site, (25-year Event; With Proposed Structures in place)

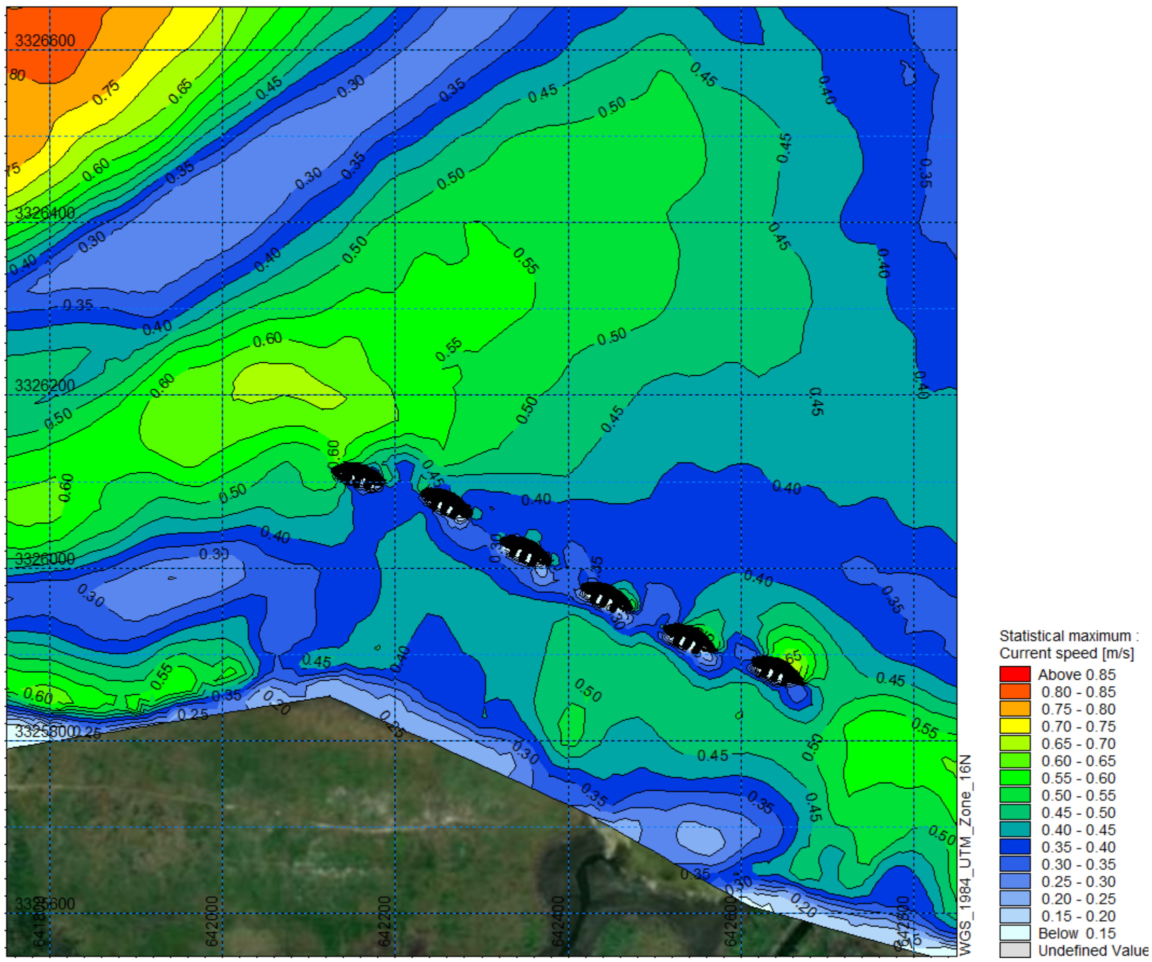


Figure A-8. Spatial Distribution of Maximum Current Speeds at the Oyster Reef Breakwater Site, (25-year, +1.96-foot SLR Event; With Proposed Structures in place)

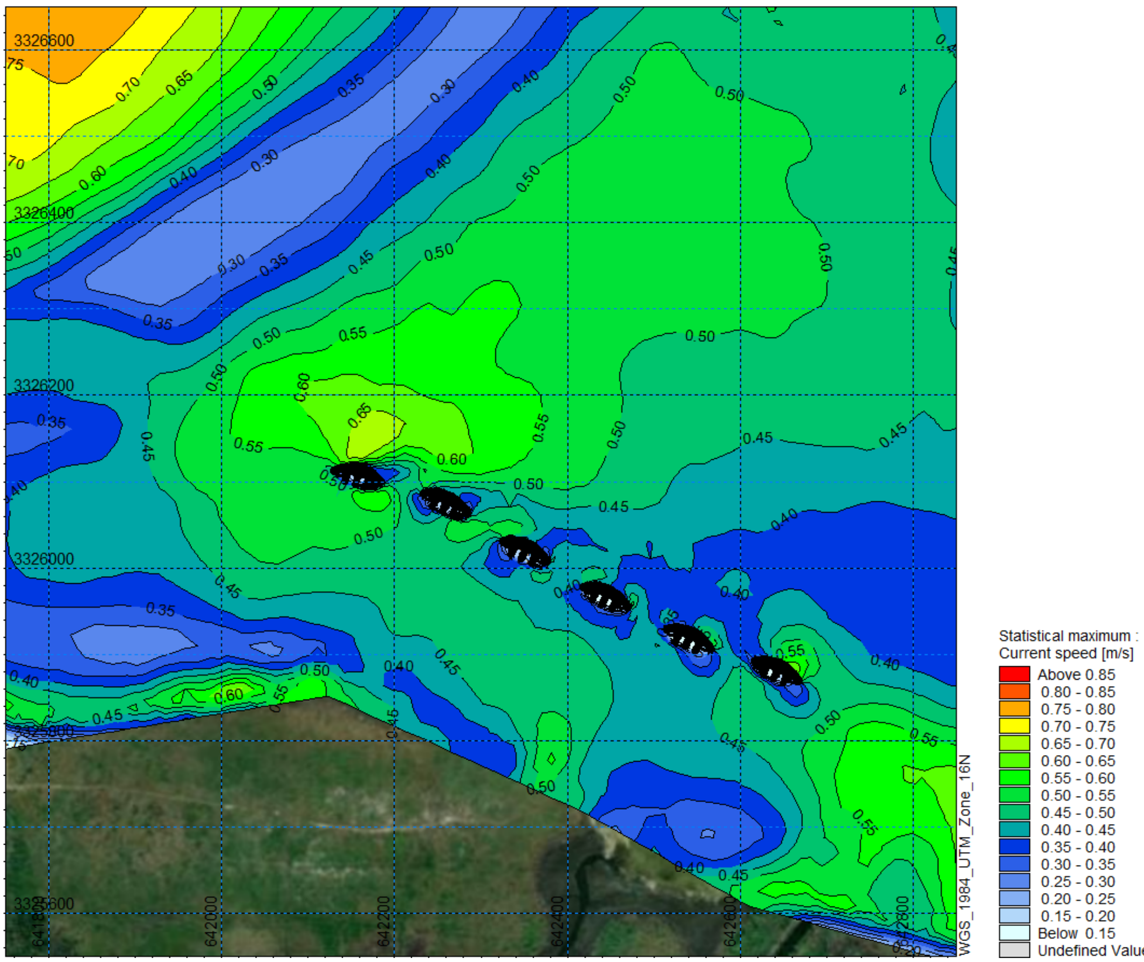


Figure A-9. Spatial Distribution of Maximum Current Speeds at the Living Shoreline Site, (25-year Event; No Structures in place)

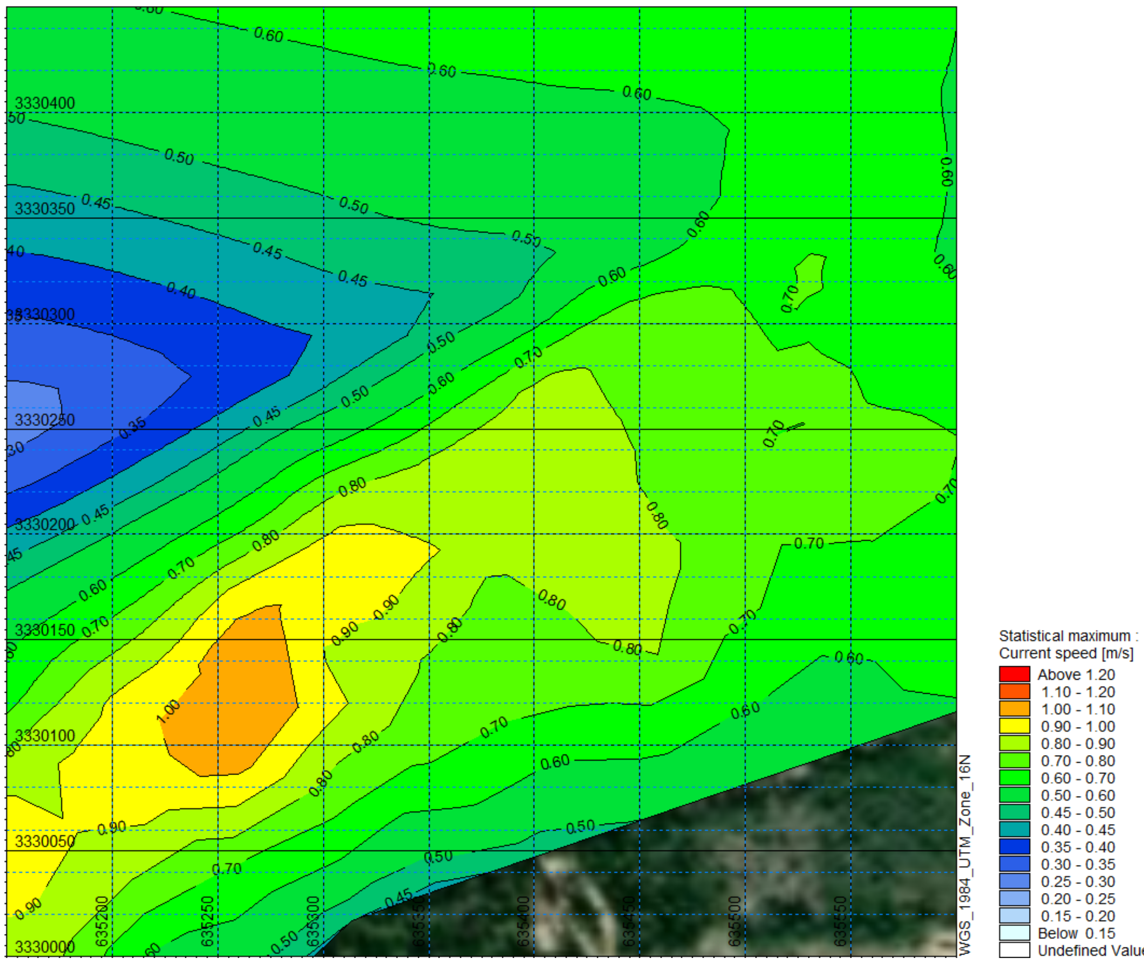


Figure A-10. Spatial Distribution of Maximum Current Speeds at the Living Shoreline Site, (25-year, +1.96-foot SLR Event; No Structures in place)

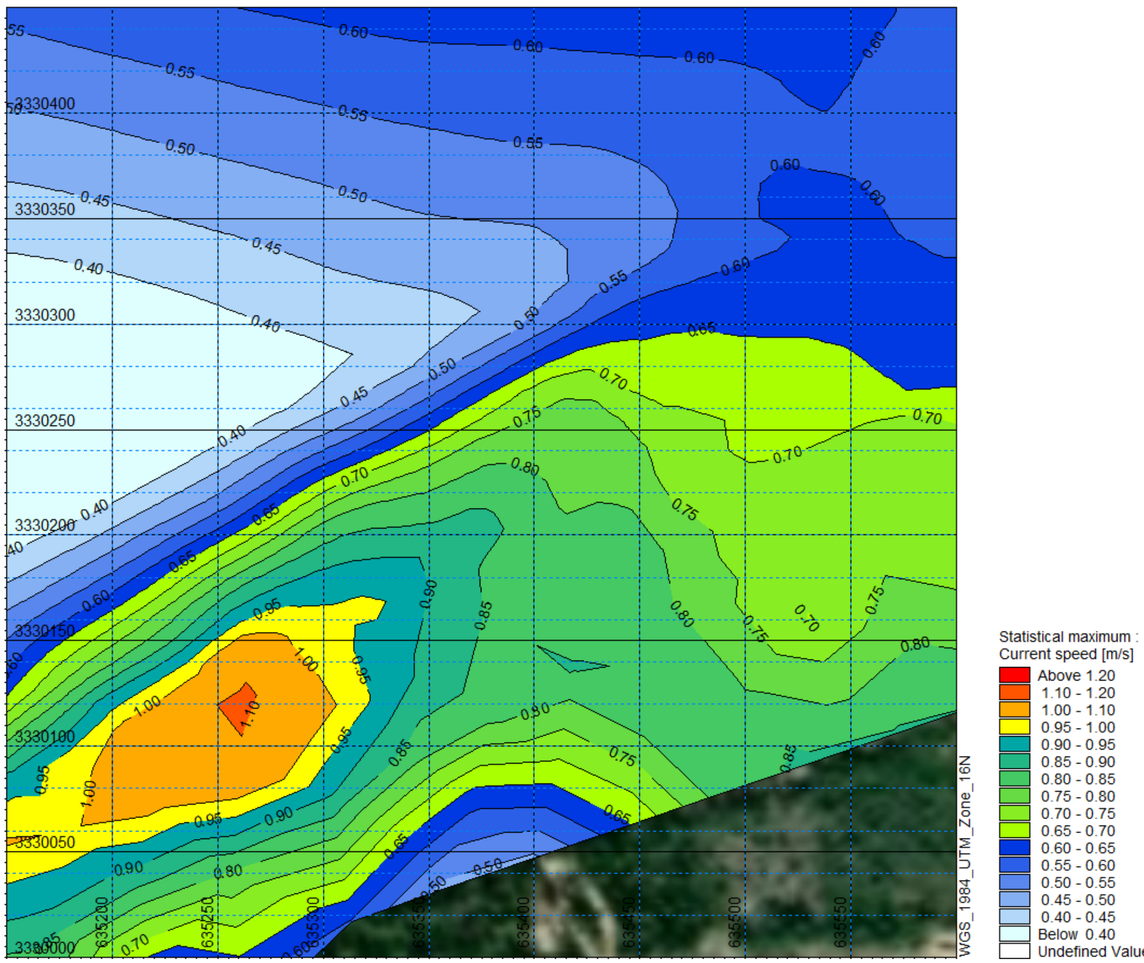


Figure A-11. Spatial Distribution of Maximum Current Speeds at the Living Shoreline Site, (25-year Event; With Proposed Structures in place)

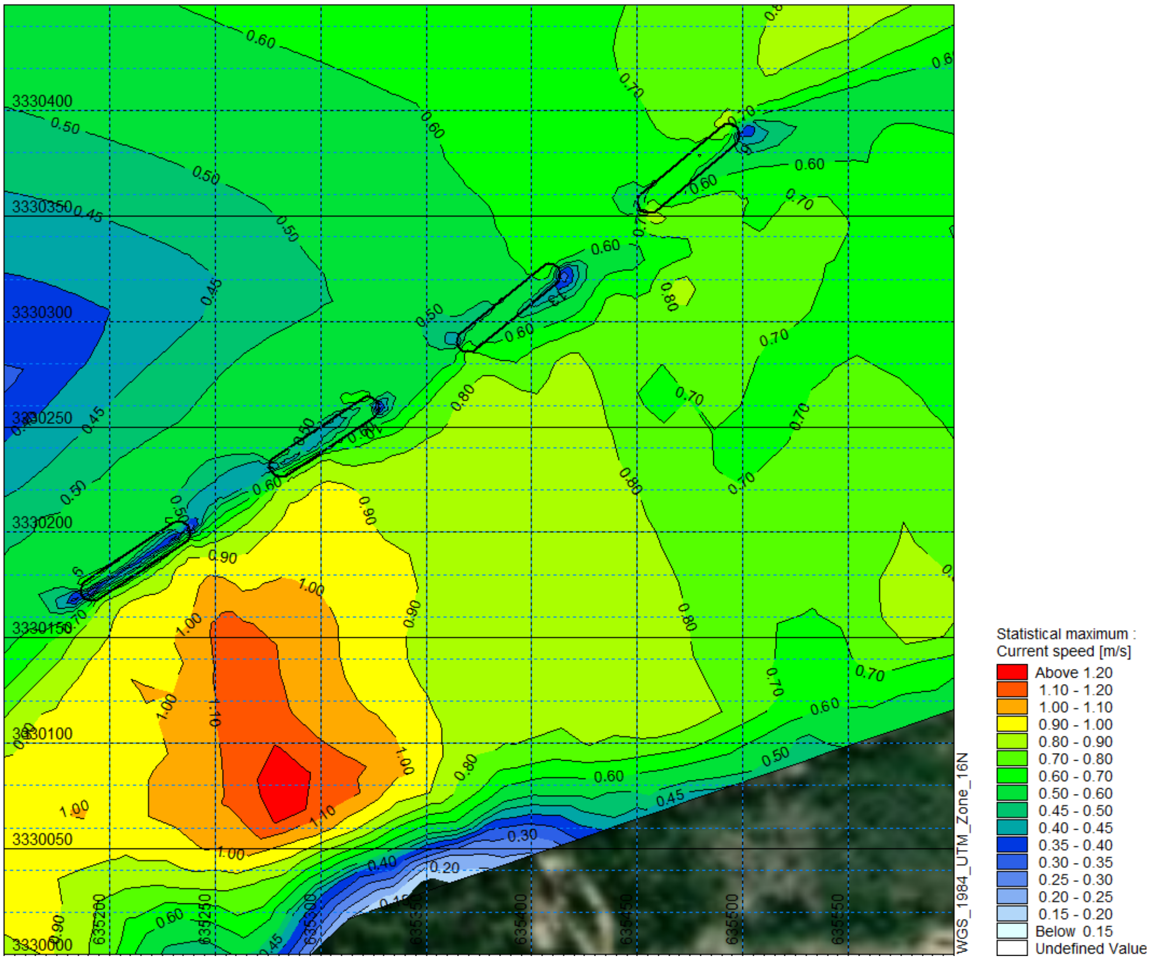
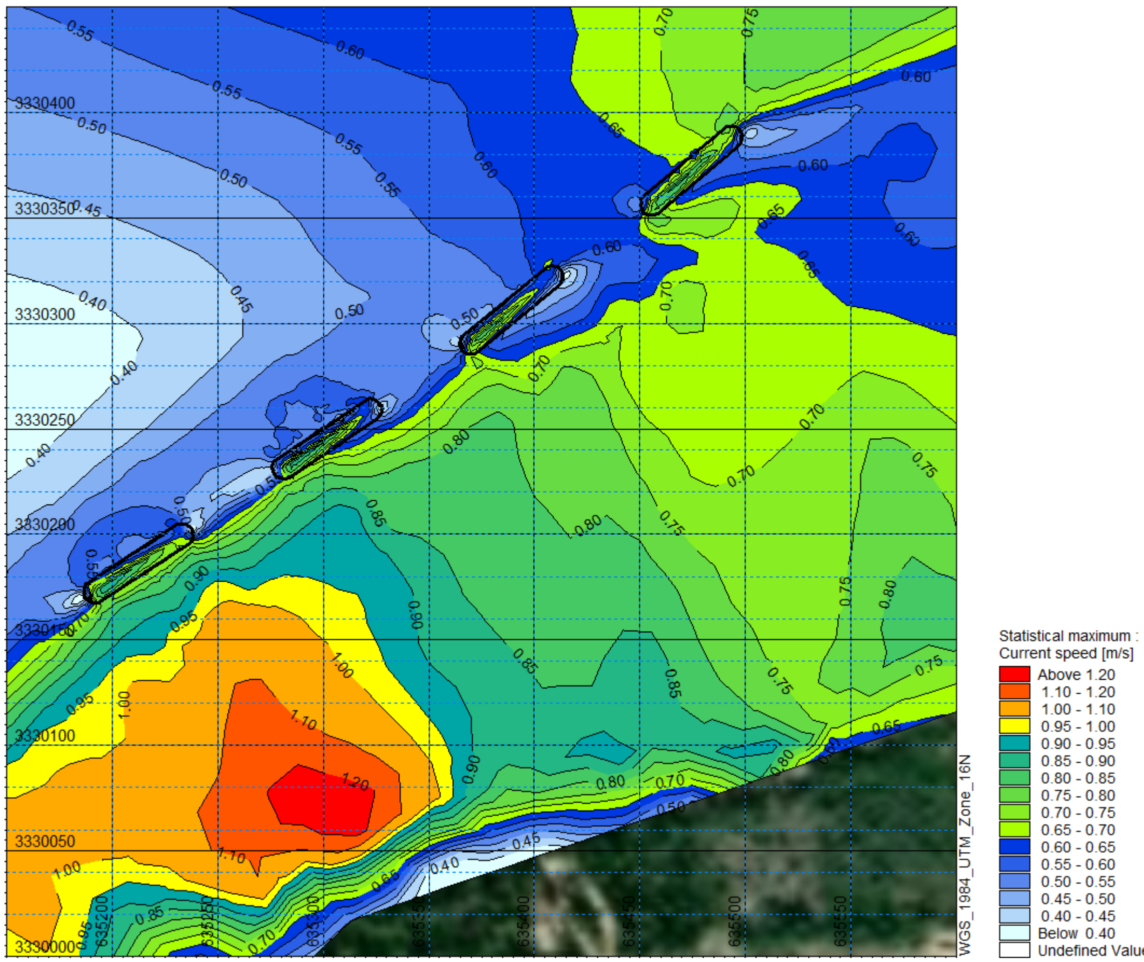


Figure A-12. Spatial Distribution of Maximum Current Speeds at the Living Shoreline Site, (25-year, +1.96-foot SLR Event; With Proposed Structures in place)



Appendix B
Plots of Spatial Distributions of Maximum Wave Heights

Figure B-1. Spatial Distribution of Maximum Wave Heights at the Submerged Shoreline Stabilization Site (50-year Event; No Structures in place)

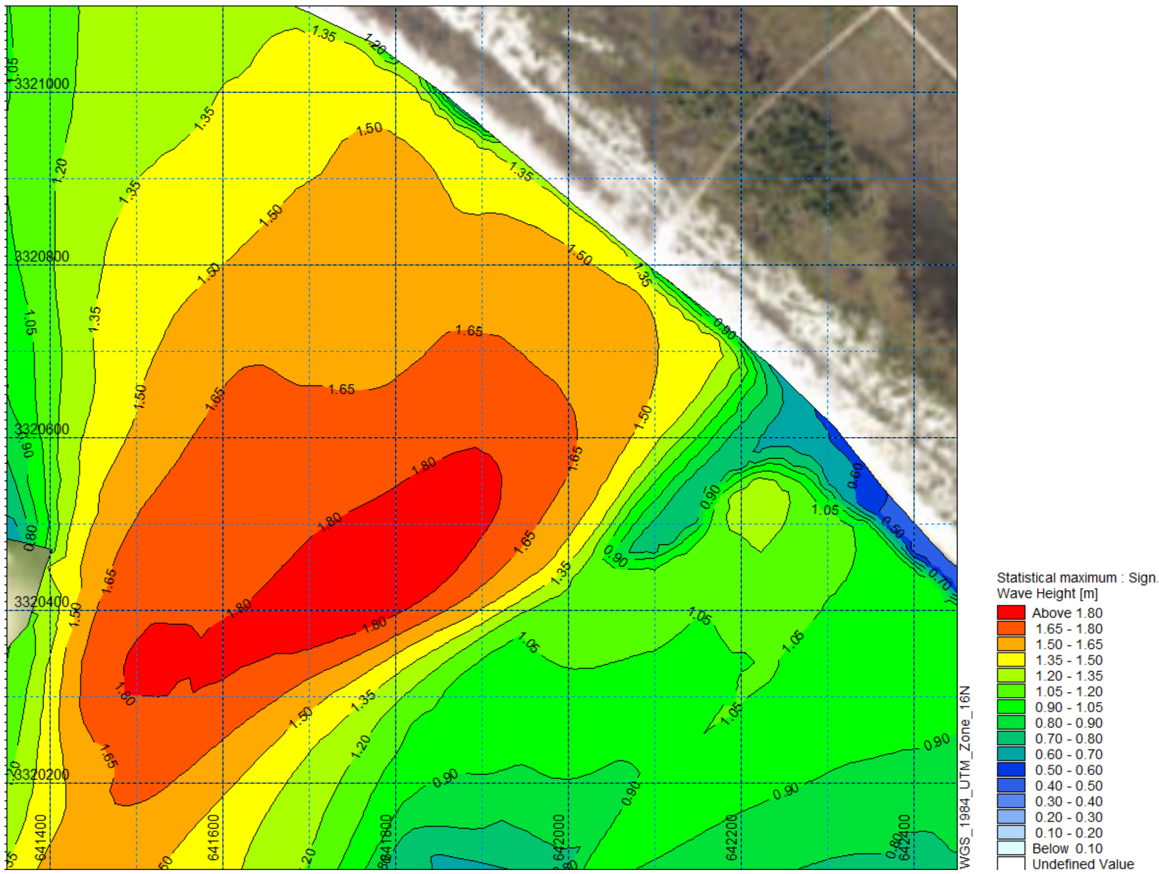


Figure B-2. Spatial Distribution of Maximum Wave Heights at the Submerged Shoreline Stabilization Site (50-year, +3.67-foot SLR Event; No Structures in place)

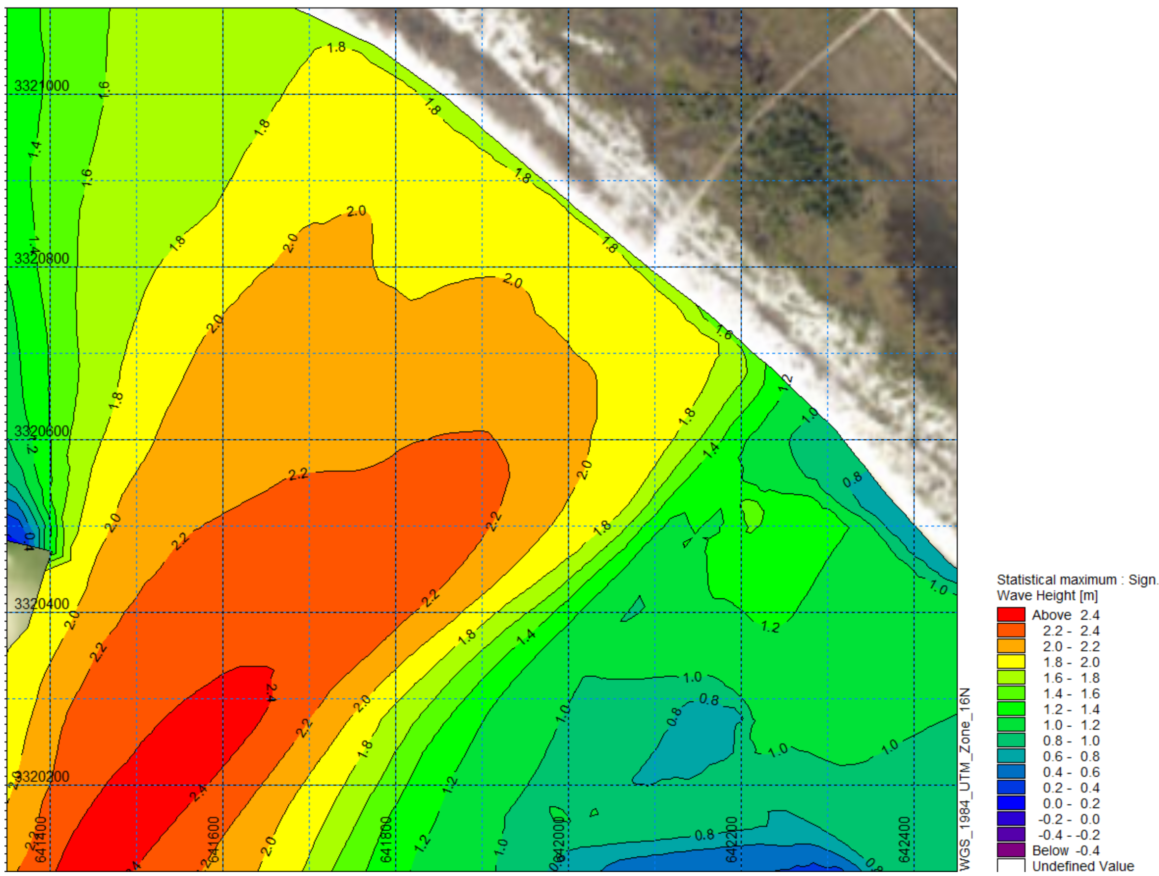


Figure B-3. Spatial Distribution of Maximum Wave Heights at the Submerged Shoreline Stabilization Site (50-year Event; With Proposed Structures in place)

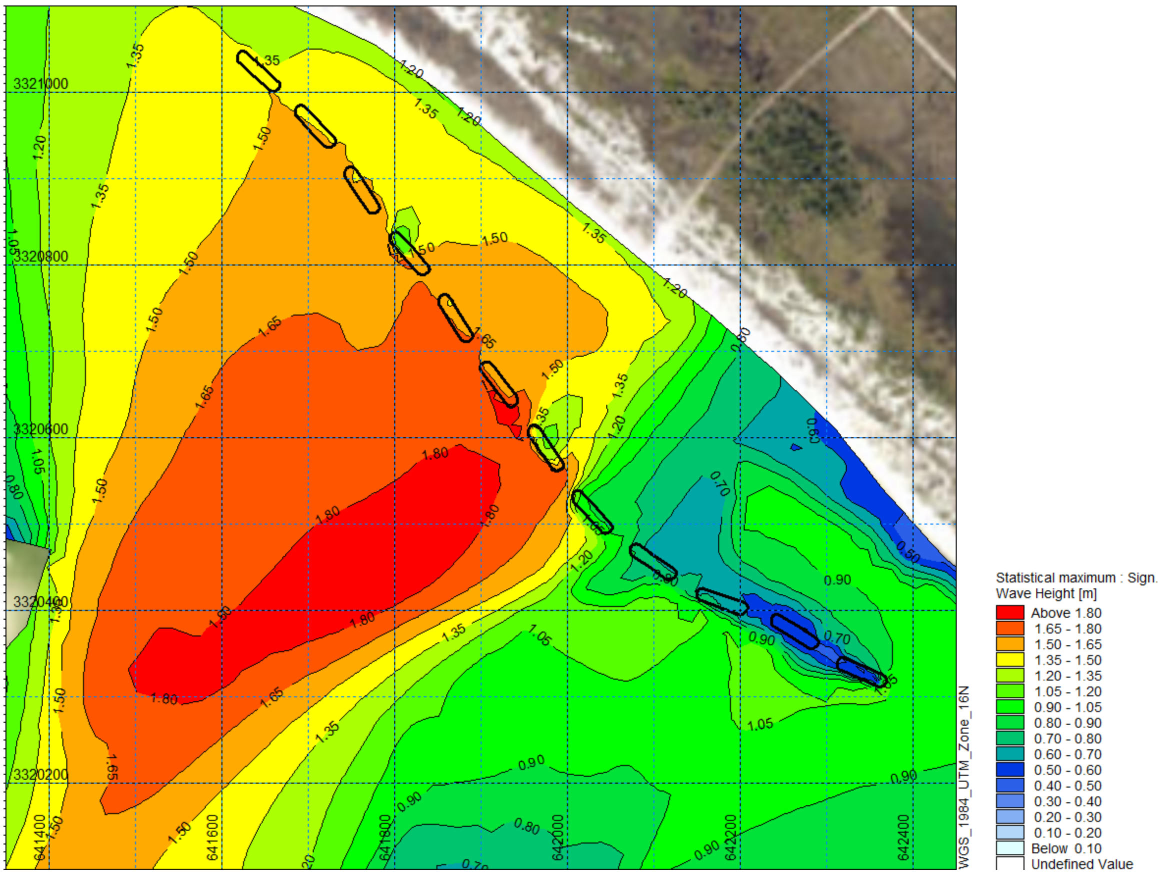


Figure B-4. Spatial Distribution of Maximum Wave Heights at the Submerged Shoreline Stabilization Site (50-year, +3.67-foot SLR Event; With Proposed Structures in place)

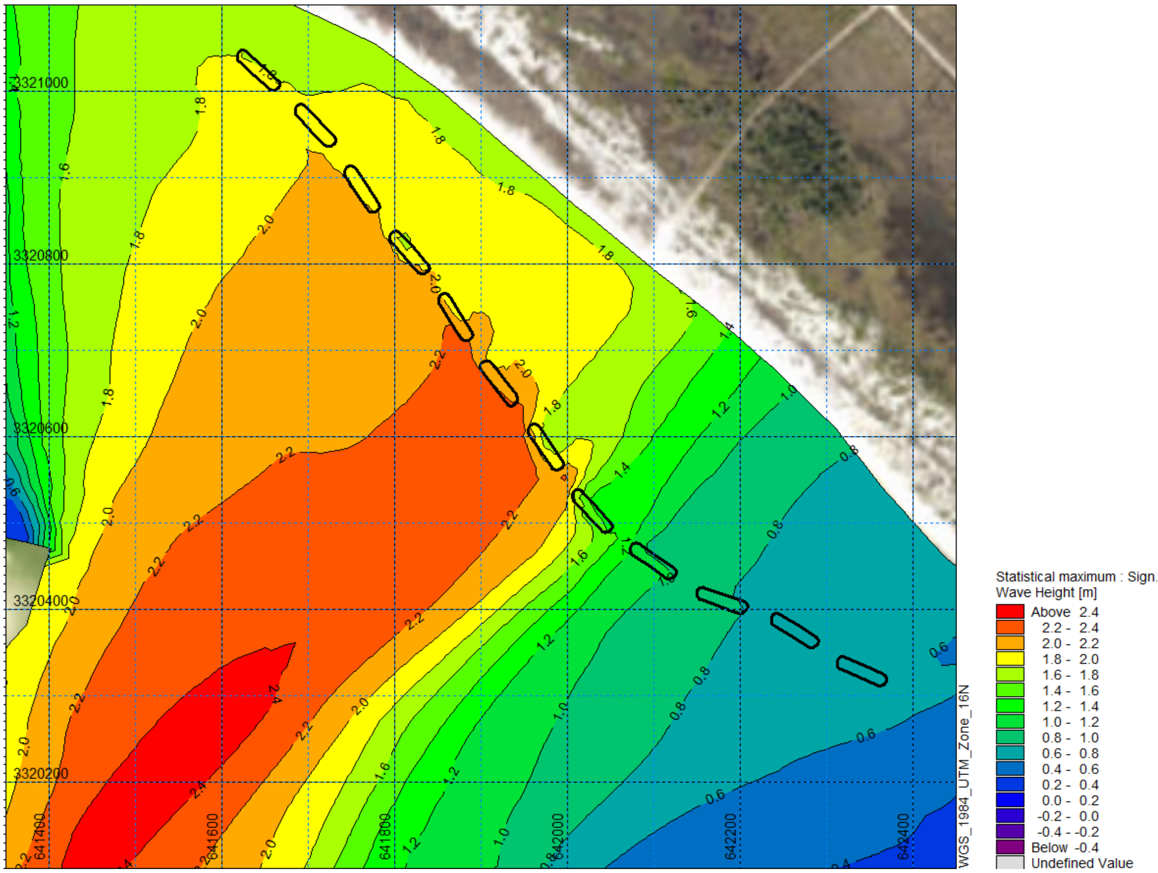


Figure B-5. Spatial Distribution of Maximum Wave Heights at the Oyster Reef Breakwater Site (25-year Event; No Structures in place)

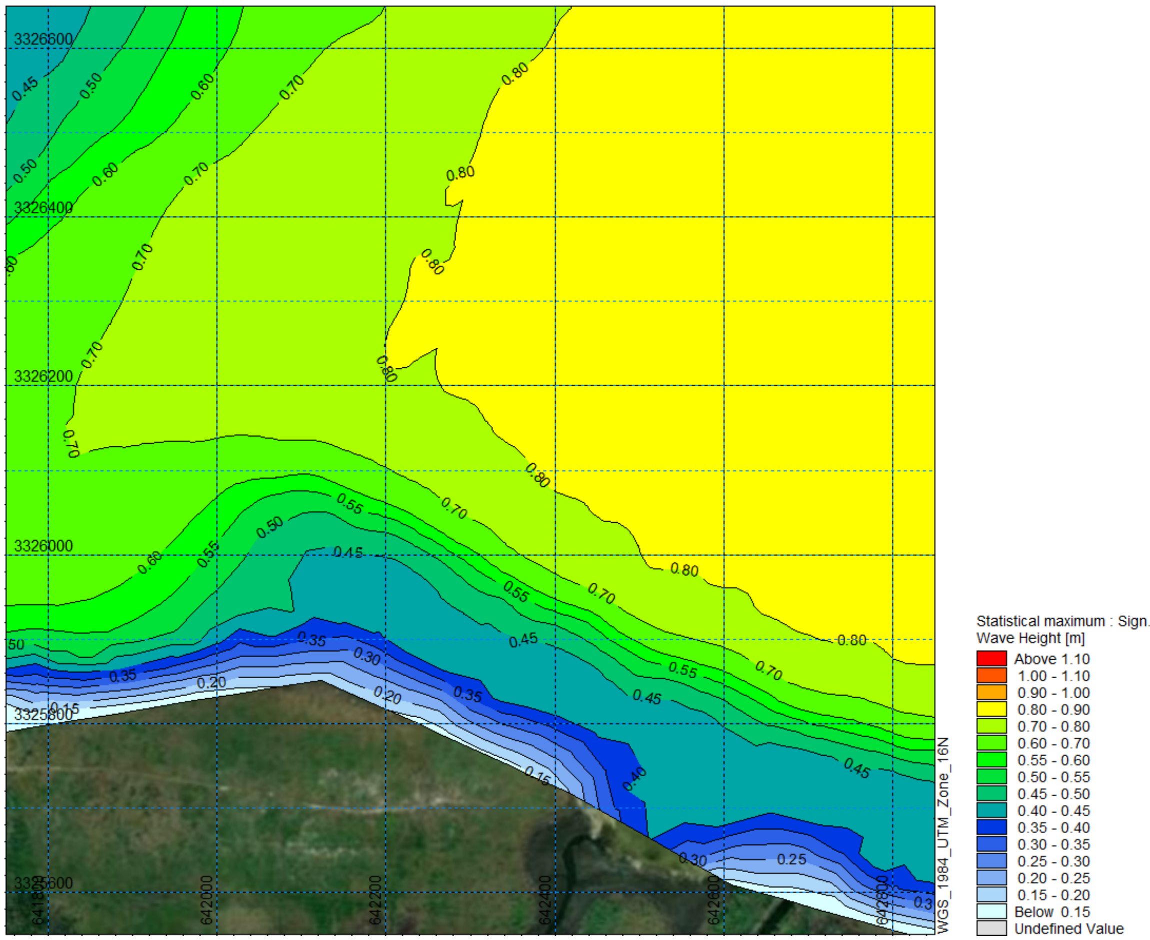


Figure B-6. Spatial Distribution of Maximum Wave Heights at the Oyster Reef Breakwater Site (25-year, 1.96-foot SLR Event; No Structures in place)

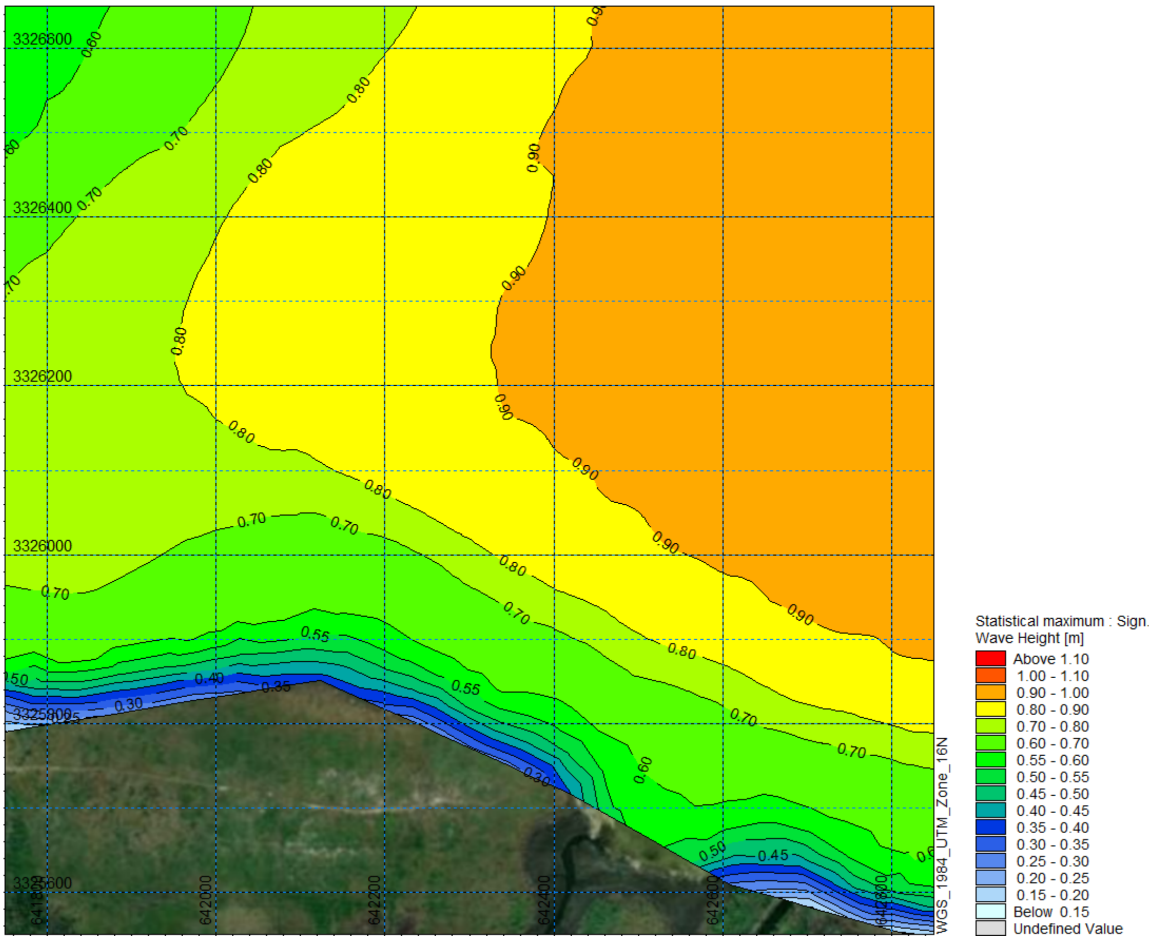


Figure B-7. Spatial Distribution of Maximum Wave Heights at the Oyster Reef Breakwater Site (25-year Event; With Proposed Structures in place)

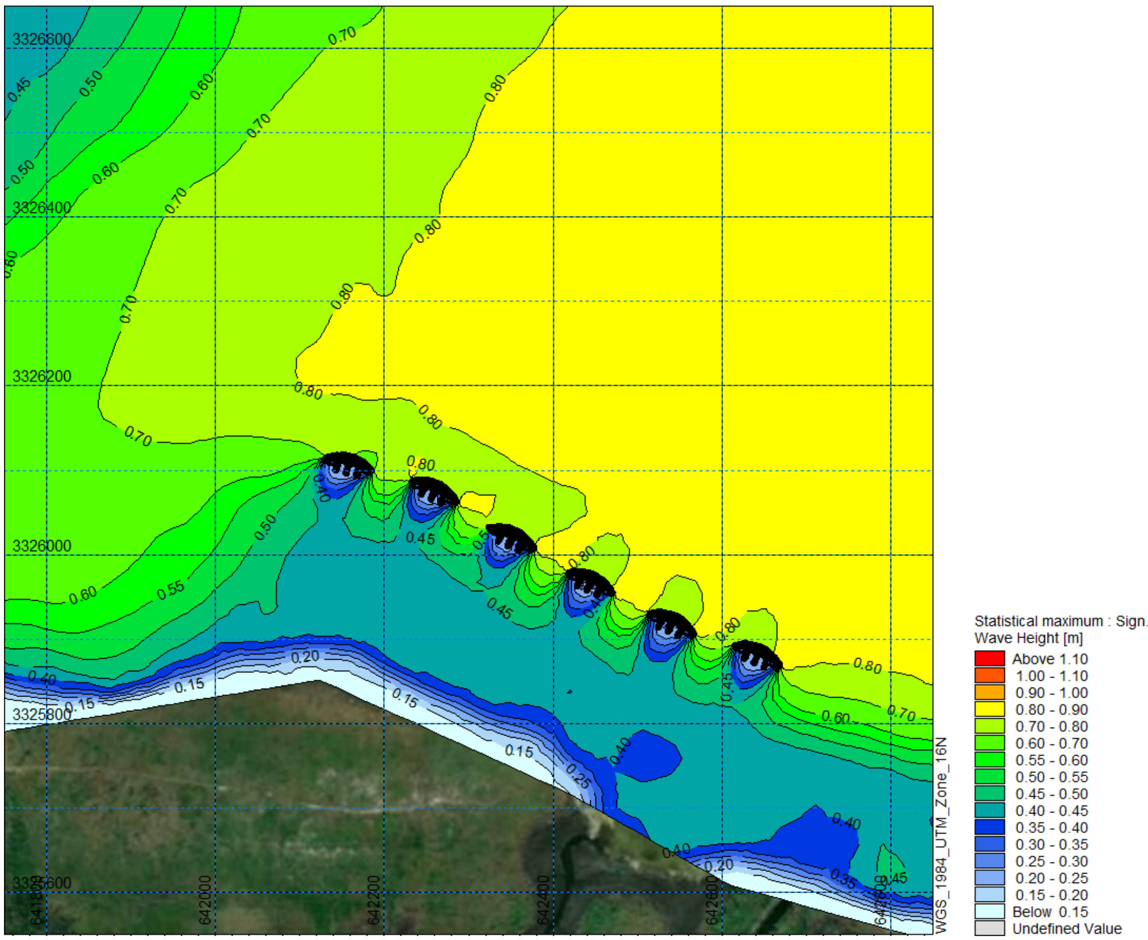


Figure B-8. Spatial Distribution of Maximum Wave Heights at the Oyster Reef Breakwater Site (25-year, 1.96-foot SLR Event; With Proposed Structures in place)

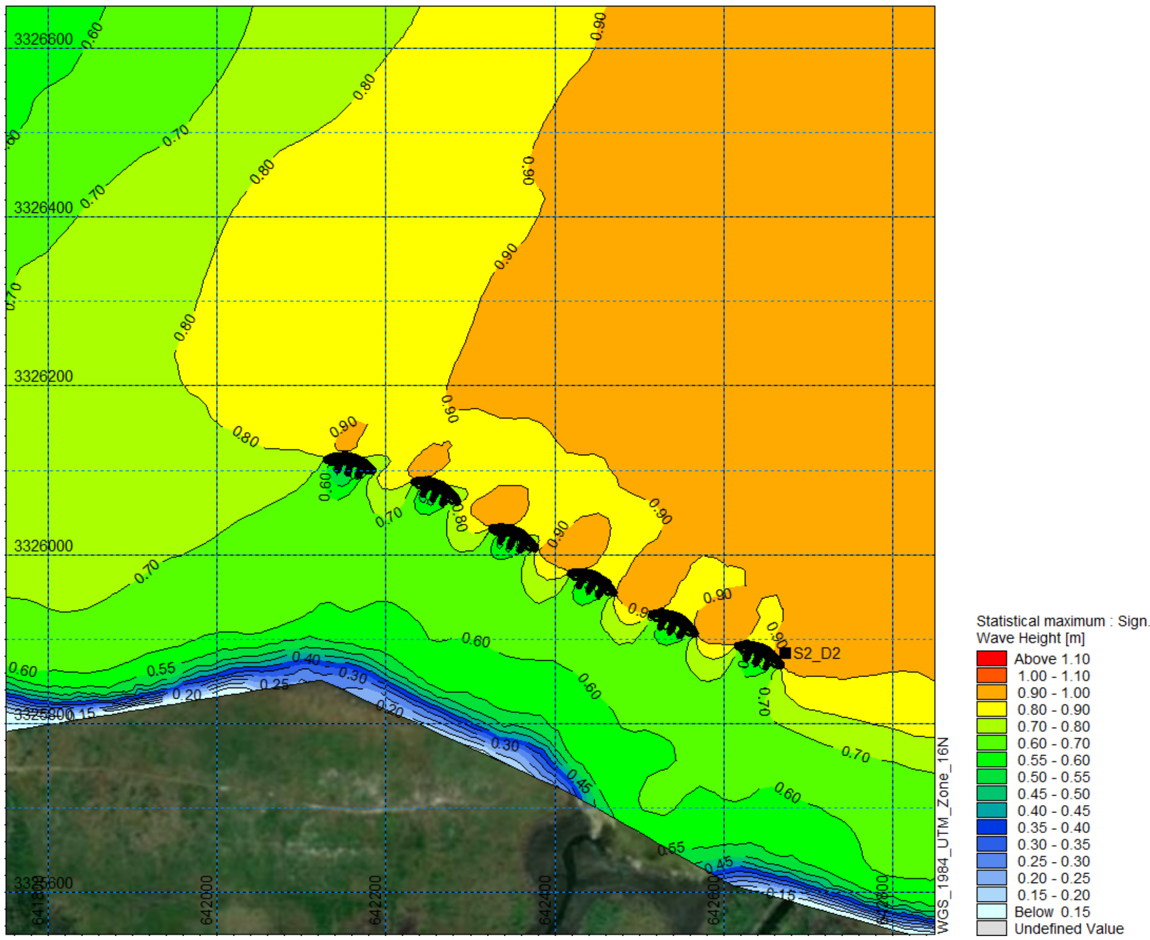


Figure B-9. Spatial Distribution of Maximum Wave Heights at the Living Shoreline Site (25-year Event; No Structures in place)

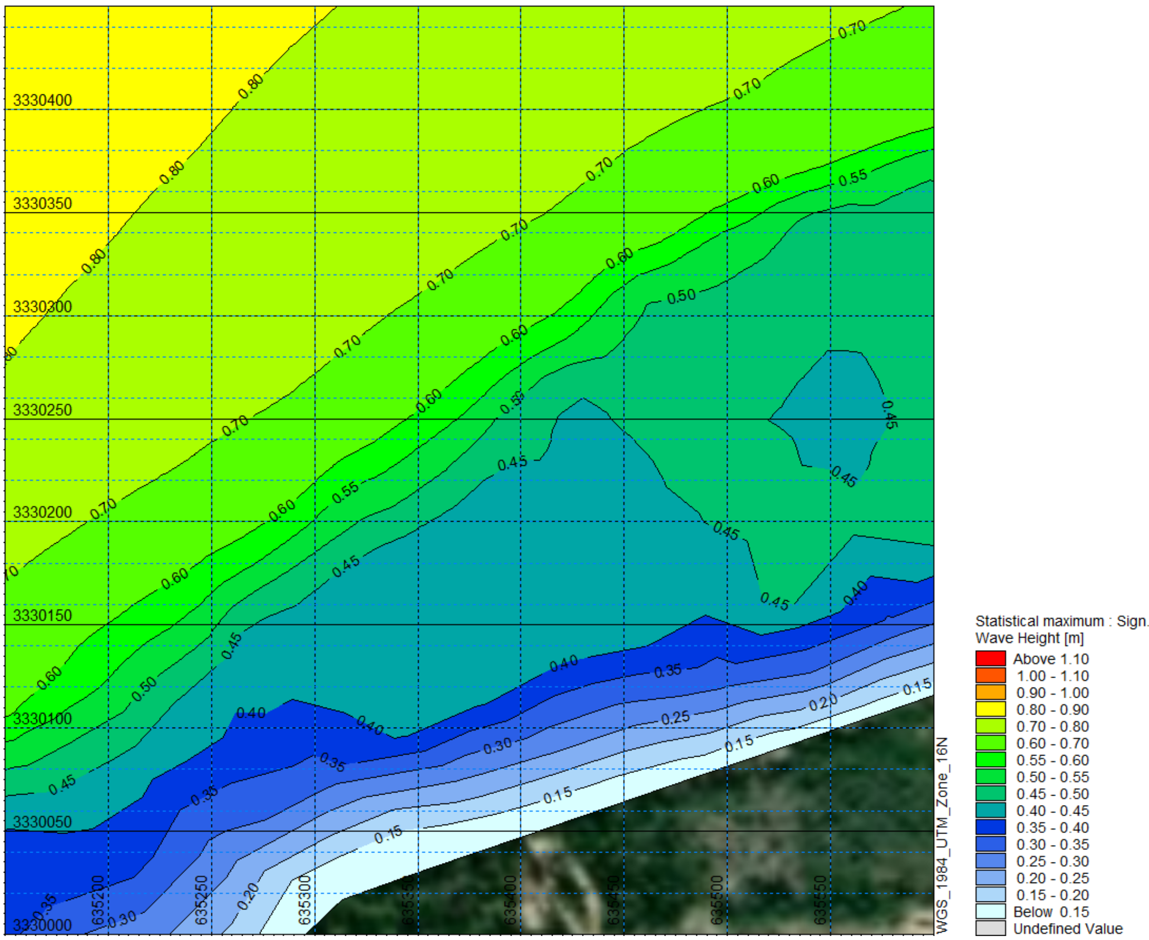


Figure B-10. Spatial Distribution of Maximum Wave Heights at the Living Shoreline Site (25-year, +1.96-foot Event; No Structures in place)

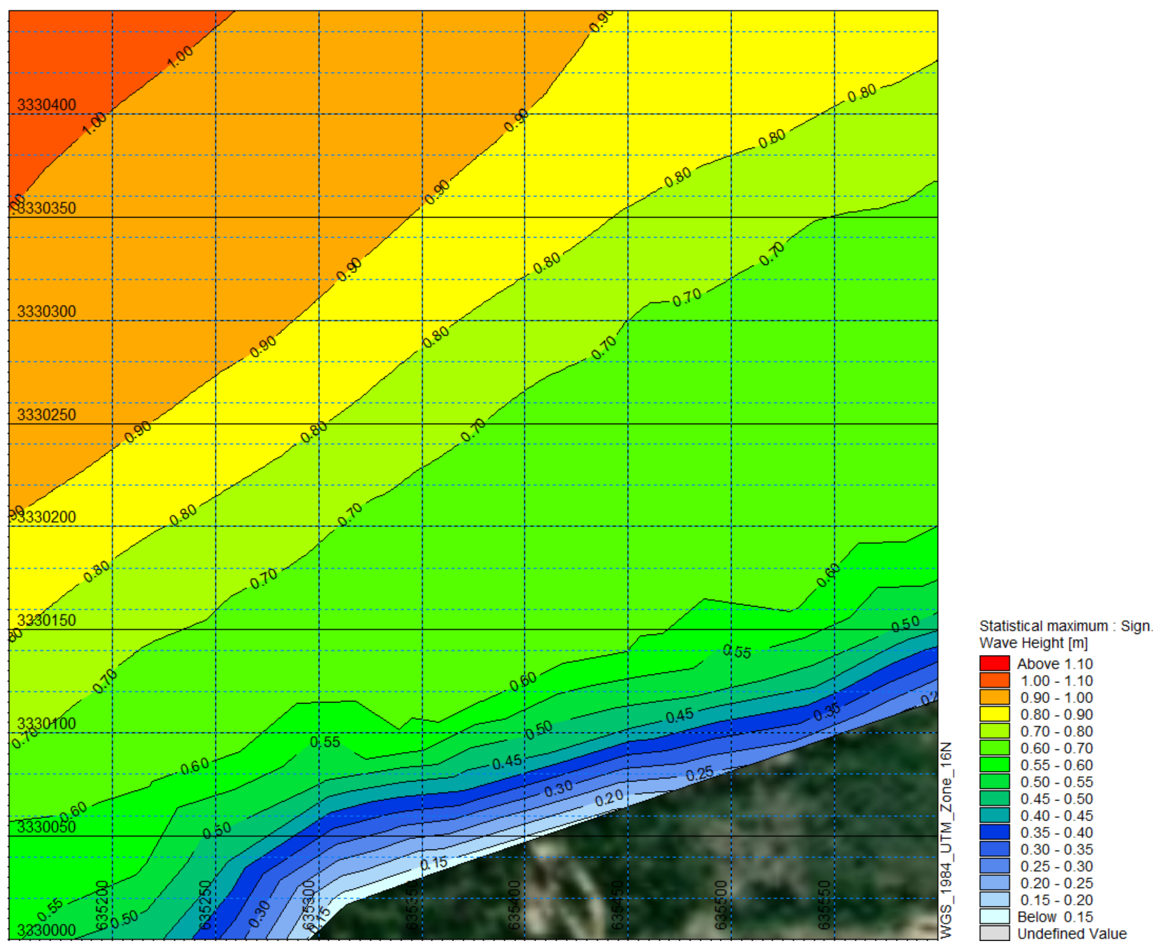


Figure B-11. Spatial Distribution of Maximum Wave Heights at the Living Shoreline Site (25-year Event; With Proposed Structures in place)

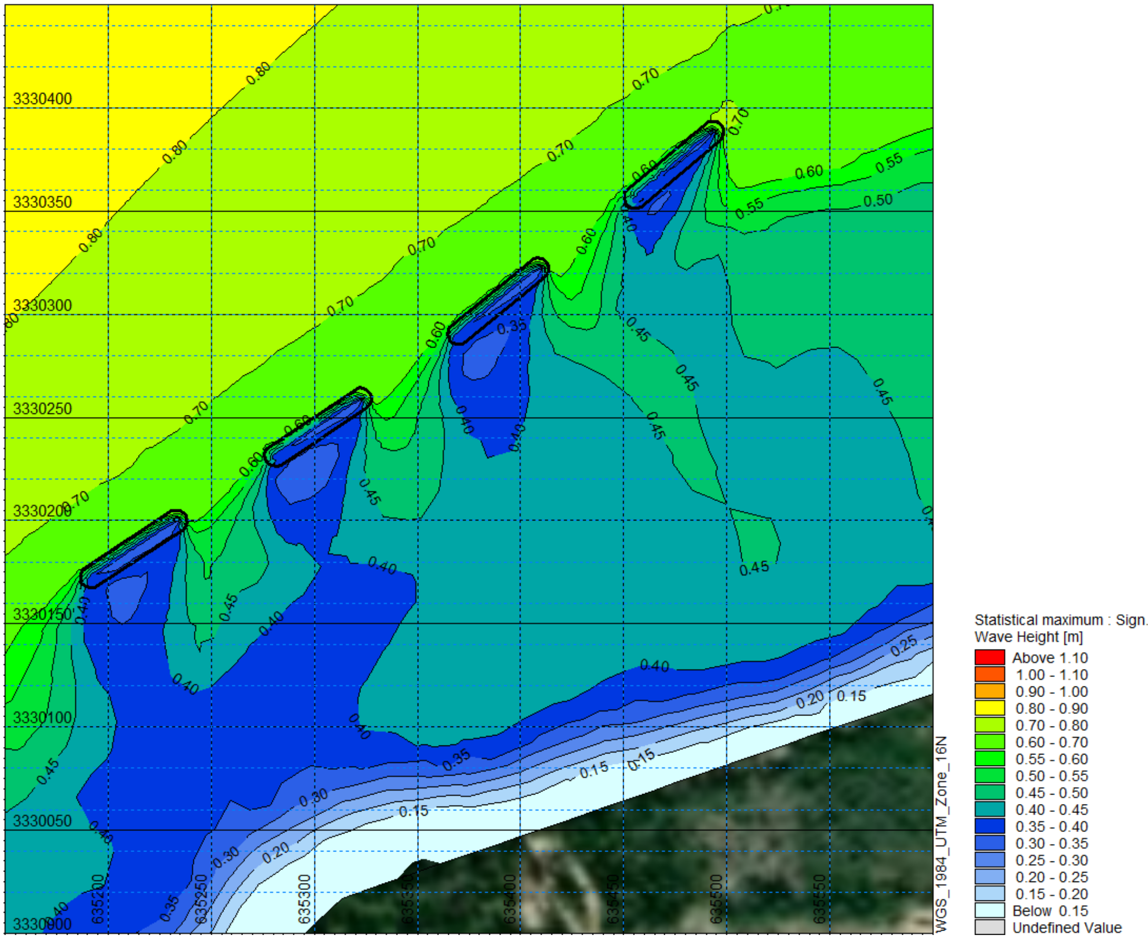
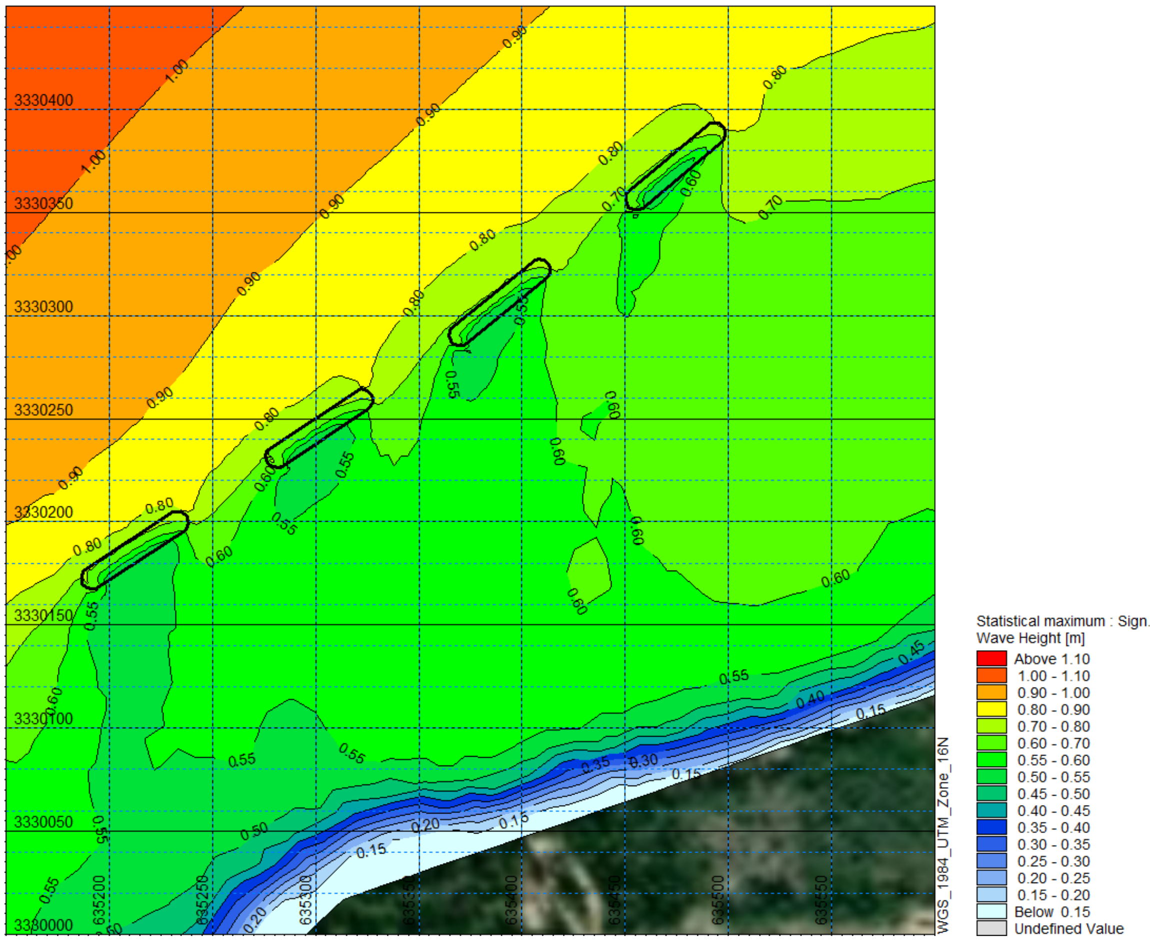


Figure B-12. Spatial Distribution of Maximum Wave Heights at the Living Shoreline Site (25-year, +1.96-foot Event; With Proposed Structures in place)



Appendix C
Geotechnical Data Report